Application of GIS in Agriculture

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GIS technology application in agriculture has gained prominence. The main GIS application areas identified included: crop yield estimation, soil fertility assessment, cropping patterns monitoring, drought assessment, pest and crop disease detection and management, precision agriculture, and fertilizer and weed management. GIS technology has the potential to enhance agriculture sustainability by integrating the spatial dimension of agriculture into agriculture policies. In addition, GIS's potential in promoting evidence-informed decision-making is growing. There is, however, a big gap in GIS application in sub-Saharan Africa. With the growing threat of climate change to agriculture and food security, there is an increased need for the integration of GIS in policy and decision-making in improving agriculture sustainability.

GIS spatial autocorrelation agri-spatial policy integration policy integration RS

1. Introduction

The demand for food globally has risen tremendously and is expected to increase to 59–98% by the year 2050 [1]. However, the growing concerns are that the agricultural food production systems are unable to match the high demand, especially in poor nations, causing an intensifying level of food insecurities [2]. The inefficiency of the food production systems is also one of the reasons for food insecurity [3]. How best to facilitate increased food production without jeopardizing land and water resources, energy, and the environment is a momentous task that government and policymakers have to address [4].

In many low- and middle-income countries (LMICs), most of the food production is rural-based, dominated by smallholder and subsistence farmers. Enhancing smallholders’ sustainability requires that farmers are empowered with practicable information that enables them not only to make evidence-informed decisions but also to implement them in activities that could increase their farm productivity and sustainability. In efforts toward transforming the weak and often inefficient traditional subsistence production practices, sustainable production approaches [5][6] that support production-efficiency-enhancement and better agronomic practices are needed. These include planting climate-resilient crops, high-yielding crop varieties, crop yield forecasting, integrated pest management, as well as integrating biodiversity solutions in sustainable food production systems [7][8] Ultimately, these novel interventions would require comprehensive, up-to-date datasets (spatial and non-spatial) and the adoption of advanced GIS technologies that can synthesize and integrate social, spatial, economic, demographic, and environmental data in agriculture. The output of this synthesis would be evidence-based spatial knowledge that improves understanding of agriculture sustainability and in supporting better policies and decision-making processes.

Contemporary advances in Geographic Information Systems (GIS), Remote Sensing (RS), and Geographic Positioning Systems (GPS) technologies present an opportunity to acquire and operationalize high-resolution satellite imagery and digital spatial data [9]. In the agriculture sector, these spatial data have aided in the investigation of the spatial linkages of social, physical, agroecological, and environmental complexities and how they affect agriculture sustainability. GIS technology provides users with a mixture of geo-spatial information management tools and methods that allow users to collect, store, integrate, query, display, and analyze geospatial data at various scales [10]. Remote sensing technology acquires images and other information about crops and soil from sensors mounted on different platforms including satellites, airborne remote sensing (manned drones and unmanned aerial vehicles), and ground-based equipment that is then processed by computers to aid agricultural decision-making systems [11][12].

The spatial context of agriculture can be viewed from the perspective of farmers' differentiated access to livelihood capitals, local resources, and access to essential infrastructure and services existing in a locality. In a GIS system, the data containing each of these aspects can be deconstructed as nested spatial layers, each rooted in local geography by geographic coordinates captured using GPS [13]. These spatial layers can then be processed and analyzed in a GIS system in multiple ways to reveal crop and soil conditions and spatial interactions, predict crop trends, monitor land-use change, monitor pests, and in biodiversity conservation [14][15][16][17]. They can also be used to map and reveal spatial impediments to agricultural production, or even new information for improving agricultural sustainability.

In recent times, the increasing complexity associated with agriculture production systems has aroused policymakers' interest in investigating how the spatial aspect "dimension" of agriculture can be exploited using advanced GIS, RS, and GPS technologies to improve agricultural productivity and better production practices [18][19]. The integration of GIS technologies in agriculture has increased the opportunities for the development of even better spatial explicit frameworks that support the creation of dynamic agriculture databases and interactive systems [20]. Such database systems allow users to interact with spatially referenced agriculture data in real-time, while accurately providing precise positional data, thus providing enhanced frameworks for decision making. New fields that apply GIS in agriculture have emerged as a result. These include precision agriculture, automated farm systems, crop yield forecasting, climate change detections, and the real-time monitoring of crop production [11][12][21]. These have the capability of improving agricultural production and food security.

In this regard, several recent systematic research have been conducted to illuminate and consolidate various ways GIS, RS, and GPS technologies have been applied in the agriculture sector. García-Berná et al. [11] used a systematic mapping study to focus on the current trend and what new opportunities in remote sensing techniques offer in agriculture. Their study found increased uptake of RS technologies in the acquisition and extracting of georeferenced data from satellite imagery and unmanned aerial vehicles. Spatial data from these technologies have been applied in several areas including crop growth and yield estimation, cropland parameter extraction, weed, and disease detection, and the monitoring of water and nutrients in plants. How this application could be integrated to improve spatial-based agriculture policymaking was not elaborated by the researchers. The Al-Ismaili [22] research highlighted the integrated application of RS and GIS techniques in precision agriculture and in the mapping, detection, and classification of the greenhouse through aerial images and satellites. How such a technique could be assimilated into enhancing policymaking was not mentioned. In yet another meta-research, Weiss et al. [12] research highlighted the emerging development in RS that strengthens the specific application of RS in crop breeding, agricultural land use monitoring, crop yield forecasting, and biodiversity loss. Sharma, Kamble, and Gunasekaran [23] focused on how GIS data applications have assisted in the development of precision agriculture. The researchers proposed a framework, "Big GIS Analytic", to guide how big GIS data should be applied in the agriculture supply chain. Their framework also lays a foundation for a theoretical structure for improving the quality of GIS data application in agriculture to elevate productivity. These studies help people to understand how GIS and RS applications in agricultural production systems have advanced. However, the available systematic research seem not to explicitly provide how GIS and RS technologies could enhance the integration of the spatial dimension of agriculture into policy frameworks and interventions.

2. Crop Yield Estimation/Forecasting

Monitoring crop growth and early crop yield forecasting over agricultural fields is an important procedure for food security planning and agricultural economic return prediction. The continued advancement in RS and GIS technologies has improved the process and techniques of monitoring the development of crops and estimating their yields [24][25][26]. Several studies demonstrate the application of integrated GIS and RS technologies in crop yield estimation. Memon et al.'s [27] study demonstrated how integrating multispectral Landsat satellite imagery and comparing different RS-based spectral indices were effective in measuring the percentage of wheat straw cover and successively determining its effect on the yields of rice crops. The knowledge can inform long-term planning of agriculture sustainability in rice-wheat cropping systems. The result of the research by Hassan and Goheer [28] showed that the accurate early estimation of wheat crop yield before harvesting can be determined by using vegetation indices derived from moderate resolution imaging spectroradiometer satellite imagery and crop yield data and the GIS modelling approach. In yet another study, Hassan and Goheer [29] used a GIS-based environment policy integrated climate model that provided a practical tool for simulating rice crop yield. The model combined regional level crop level data, soil data, farm management data, and climatic data to spatially estimate variations in crop yield. Likewise, Al-Gaadi et al. [25] extracted the normalized difference vegetation index and soil-adjusted vegetation index from Landsat satellite images acquired during the potato growth stages to predict potato tuber crop yield. GIS- and RS-based crop yield forecasting models could have a wider application in informing spatially based agriculture policies. For example, based on the output of these models, policy intervention can be designed to manipulate the specific contributors to crop yields (which include farm management techniques, weather conditions, water availability, altitude, terrain, plant health, and policy intervention) [30][31]. Forecasting crop yields well before harvest is crucial, especially in a region characterized by climatic uncertainties. Monitoring agricultural crop growth conditions and the prediction of potential crop yield is important in planning and policymaking for food security and agricultural economic return prediction [24][26][29]. This could include developing policies for improving agriculture productivity and sustainability [29]. In feeding a growing population in LMICs, agricultural production systems must strive to reduce the food production yield gap between current yields achieved by farmers and those potentially attainable in rainfed subsistence farming systems. In addressing this mismatch, the study by Hochman et al. [31] developed a model that integrated statistical yield and cropping area data, remotely sensed data, cropping system simulation, and GIS mapping to assess and map wheat yield gaps.

3. Soil Quality/Fertility Assessment

Soil quality assessment is critical for designing sustainable agricultural practices (optimal agricultural use) that can help bridge the current food production and demand gap in overcoming the food security problem. The availability of RS datasets and GIS spatial modelling techniques provides new opportunities for measuring/evaluating soil quality at different spatial scales [32][33]. Shokr et al. [34] developed a spatially-explicit soil quality model by combining soil's physical, chemical, and biological properties and integrating these with a digital elevation model and Sentinel-2 satellite image to produce digital soil maps. Abdelfattah and Kumar [35] describe the application GIS-enabled web-based soil information system that provides a descriptive, quantitative, and geospatial soil database in a simple interface. The system was applied to determine the sufficiency potential of soils for plant growing and management. Using GIS and RS technologies, Abdellatif et al. [36] developed a spatial model for the assessment of soil quality. His model combined four main soil quality indices (soil fertility index, soil physical index, soil chemical index, and geomorphological properties Index) and GIS ordinary kriging spatial interpolation to map the soil quality index. The application of these GIS-based models provides evidence-based ways to improve soil quality management. This would enable decision makers, policy formulators, land-use planners, and agriculturalists to efficiently manage soil resources to ensure the sustainable use of agricultural lands according to their potential [33][37][38]. Thus, assessing soil quality indicators would be important for sustainable agricultural policies and practices and in achieving food security.

4. Crop Mapping and Monitoring Decision Support Systems

In an era of unpredictable climate changes, agricultural crop monitoring analysis could help government policymakers and farmers plan and design cropping patterns that adapt to water availability. Agricultural monitoring systems integrate multiple geospatial data sets and cropping system models into computer algorithms to spatially compute and simulate optimum scenarios for site-specific conditions for crop production [39]. A crop monitoring system is developed by integrating geospatial data obtained by high-resolution remote sensing with a web GIS geoportal interface [40]. Santosh and Suresh [41] demonstrated the uniqueness of combining GIS and RS in a tool for crop selection and rotation analysis at the farm level to improve crop management decisions. Cropping patterns simulation is determined by irrigation water availability, which in turn is affected by changes in climate and irrigation water extraction policies. Wang et al. [16] combined GIS and irrigation water availability simulation models to analyze the cropping patterns based on the forecast of irrigation water availability. A GIS web-based crop mapping and monitoring decision support system at the farm level could help farmers to access information and take appropriate measures to improve crop production [41]. Such a system can have a wider application in supporting agronomic decision making including optimizing land and labor productivities, enhancing higher cropping intensities, and producing better crop yield [42]. This can increase crop production and ensure better crop management, in the long run, and precision irrigation management.

5. Agricultural Drought Assessment

Using spatial datasets generated by satellite RS and GIS technologies offers very useful information for assessing and modelling agricultural drought-risk patterns, monitoring drought conditions, and producing drought vulnerability (risk) maps [43]. Hoque et al. [44] integrated geospatial techniques with fuzzy logic to develop a comprehensive spatial drought risk inventory model for operational drought management. This model successfully identified the spatial extents and distribution of agricultural drought risk. Sehgal and Dhakar [45] used GIS and high spatial resolution RS-derived indicators of crop sensitivity to develop a methodology that assessed and mapped, at a local scale, key biophysical factors contributing to agricultural drought vulnerability. The drought vulnerability maps could inform policymakers in formulating spatially explicit policies for drought mitigation and intervention strategies [46][47]. In addition, vulnerability maps could be used to indicate where socioeconomic development policy programs should be given priority [48].

6. Pest and Crop Disease Detection and Management

Several geospatial tools and techniques continue to be developed to aid farmers in crop disease control and management strategies. Several studies [49][50][51][52] provide practical application of satellite RS data and Geospatial techniques for sustainable crop disease detection and management. RS technology including Airborne and satellite imagery acquired during growing seasons has been used for early- and within-season detection, mapping of some crop diseases, the control of recurring diseases in future seasons, and assessing economic loss caused by frost damage [49]. Santoso et al. [50] used high-resolution QuickBird satellite imagery to effectively detect spatial patterns of oil palm plants infected by basal stem rot disease. They used six vegetation indices derived from visible and near-infrared bands of satellite imagery to successfully discriminate between healthy and infected oil palms. Using precision agriculture technologies and remotely sensed imagery, Yang [52] showed how site-specific fungicide application to disease-infested areas has been implemented for effective control of the disease. In the future, new approaches that apply geoinformation technologies in monitoring and management of pest and crop disease detection could reduce the effect of pesticides and herbicide chemicals on the environment.

7. Precision Agriculture

In precision agriculture, automated geospatial analysis and decision support algorithms can provide valuable scientific information to policymakers for better agriculture policy development. Precision agriculture practices, which employ integrated GIS, RS, and GPS technologies, have gained prominence in their ability to optimize crop production, facilitate site-specific crop management, and reduce the application of agrochemicals. Toscano et al. [53] demonstrated the usefulness of Sentinel-2 and Landsat-8 images to depict the within-field spatial variability of wheat yield, which is key for adopting precision farming techniques. This provided a potential alternative to traditional farming practices by improving site-specific management and agricultural productivity. García et al. [54] tested the performance of remote sensing drones as mobile gateways to provide a guide to the optimal drone parameters for successful Wi-Fi data transmission between sensor nodes and the gateway in precision agriculture systems. The study successfully demonstrated that drones (flying at the lowest velocity, at a height of 24 m, and with an antenna with 25 m of coverage) can be used as a remote sensing tool to gather data from the nodes deployed on the fields for crop monitoring and management. This had the potential to increase the adoption of precision agriculture by even smallholder farmers. Segarra et al.'s [55] study specifically focused to understand the European Space Agency's twin Sentinel-2 satellites' features and their application in precision agriculture. Their study highlights that Sentinel-2 has dramatically increased the capabilities for agricultural monitoring and crop management, abiotic and biotic stress detection, improved the estimation of crop yields, enhanced crop type classifications, and provided a variety of other useful applications in agriculture. All of these contribute to increasing the adoption of precision agriculture, which leads to more productive and sustainable agriculture management and environmental sustainability [56][57]. In precision agriculture, plantation-rows extraction using satellite image-based solutions is essential in crop harvesting, pest management, and plant grow-rate predictions. The study of Fareed and Rehman [58] used GIS and RS to design an automated method to extract plantation rows from a drone-based image point clouds-based digital surface model. The automatic plantation rows extraction can be used to quantify plantation-row damage assessment in precision agriculture.

8. Weed Management and Fertilizer Decision Support System

Accurate weed distribution mapping could greatly enhance efficiency in weed management and reduce weed damage, overhead costs of herbicide application, and the rationalization of fertilizers [59]. Dunaieva et al. [21] used GIS technologies to produce accurate weed distribution maps in rice farms. This information improved the efficiency of input application, thus reducing the consumption of inputs including herbicides, fungicides, and weeding labor costs. This in turn reduced the weed damage and crop production overhead costs. Xie et al. [60] demonstrated the application of GIS in the development of a GIS-based Fertilizer Decision Support System (FDSS) by integrating RS data, field surveys, and expert knowledge to develop a soil spatial database on the SuperMap platform for crop management systems. The application of FDSS in agricultural production had benefits, such as increasing fertilizer utilization efficiency, thus lowering production costs.

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