Czech University of Life Sciences Prague
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http://online.agris.cz

ISSN 1804-1930
XVII, 2025, 1

International scientific journal
Prague

Agris on-line Papers in Economics and Informatics

The international reviewed scientific journal issued by the Faculty of Economics and Management of the Czech University of Life Sciences Prague.

The journal publishes original scientific contributions from the area of economics and informatics with focus on agriculture and rural development.

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Publisher

Faculty of Economics and Management
Czech University of Life Sciences Prague
Kamýcká 129, 165 00 Praha-Suchdol
Czech Republic
Reg. number: 60460709

ISSN 1804-1930

XVII, 2025,
30th of March 2025
Prague

Agris on-line
Papers in Economics and Informatics

ISSN 1804-1930

XVII, 2025, 1

Agris on-line Papers in Economics and Informatics

Volume XVII Number 1, 2025

Content:

Volume XVII Number 1, 2025

Precision Crop Farming Framework for Small-Scale Rainfed Agriculture Using UAV RGB High-Resolution Imagery

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Abstract

This paper presents a precision crop farming framework developed for small-scale rainfed agriculture using unmanned aerial vehicle (UAV) red, green, and blue (RGB) high-resolution imagery. The aim is to enhance farm management by providing precise spatial and temporal information in heterogeneous farming systems in Botswana's semi-arid regions. The precision crop farming framework integrates UAVs and Global Navigation Satellite System (GNSS) data, introducing new vegetation indices and employing machine learning algorithms for high-accuracy crop and land use analysis. The framework comprises four components: data collection, applications, data processing, and users. Methods included UAV data acquisition, global navigation satellite system geo-referencing, and machine learning classification. Results demonstrated high spatial resolution and classification accuracy, providing actionable insights into crop conditions, planting patterns, and farm variability. The precision crop farming framework is a tool for improving agricultural productivity and sustainability, providing a foundation for efficient, data-driven farm management practices.

Keywords

Unmanned aerial vehicle imagery, small-scale rainfed architecture, geospatial information system, machine learning, remote sensing.

Bolo, B., Zlotnikova, I. and Mpoeleng, D. (2025) "Precision Crop Farming Framework for Small-Scale Rainfed Agriculture Using UAV RGB High-Resolution Imagery", *AGRIS on-line Papers in Economics and Informatics*, Vol. 17, No. 1, pp. 3-19. ISSN 1804-1930. DOI 10.7160/aol.2025.170101.

Introduction

Sub-Saharan Africa faces severe food insecurity and malnutrition, with nearly 282 million undernourished people in 2022 (FAO, 2023). The region's agriculture, crucial for the economy and employing most of the population, is dominated by small-scale, irregular subsistence farms (Tscharntke et al., 2012). Challenges include food security issues exacerbated by population growth (Blizkovsky and Emelin, 2020), unsustainable land use, and socio-cultural factors contributing to poverty (Apata et al., 2021). Precision farming, utilizing technologies like UAVs, offers data-driven decision support for effective farm management, essential for managing both small and large-scale farms (Finger et al., 2019; Wolfert et al., 2017). Sustainable intensification and climate-smart agriculture enhance productivity and resilience, addressing food production challenges under unreliable climate conditions (Campbell et al., 2014). Exploring precision farming technologies could significantly improve agricultural productivity in Africa (Bolo et al., 2019; McCarthy et al., 2023).

UAV use in precision agriculture

UAVs have emerged as vital tools in precision agriculture, offering several advantages over satellites, particularly in their ability to navigate complex landscapes, operate at high speeds, and provide precise localization data (Gao et al., 2023a). UAVs bridge the spatial resolution gap between ground observations and satellite sensors, making them effective for crop monitoring in small-scale farming environments (Nduku et al., 2023).

One of the most significant advantages of UAVs is their ability to capture high-resolution images, which allows for detailed observation of small-scale features within fields, such as individual plants (Lee et al., 2023; Lin et al., 2023), weeds (Mohidem et al., 2021; Furaste Danilevicz et al., 2023), and signs of disease (Soares da Silva et al., 2022; Yağ and Altan, 2022). This high level of detail is crucial for tasks like crop health monitoring, where immediate data collection is often required to address time-sensitive issues such as pest infestations or damage from weather events (Bouguettaya et al., 2022; Ma et al., 2022a; Bai et al., 2024; García-López et al., 2022).

UAVs also enable real-time data collection and analysis, which is critical for making prompt management decisions. Unlike satellites, which have limited revisit times and lower spatial resolution, UAVs can be deployed on demand, offering the flexibility needed for frequent monitoring. This capability is particularly beneficial for assessing crop growth and predicting yields, as demonstrated in studies focusing on crops like maize, rice, and soybeans (Li et al., 2022; Guo et al., 2022; Zheng et al., 2022; Hassani et al., 2023; Killeen et al., 2024).

For instance, Ma et al. (2023a) utilized UAVs to monitor summer maize growth while Ma et al. (2023b) predicted field-scale winter wheat. Both studies used multimodal imagery. Similarly, Lee et al. (2023) combined UAV data with deep learning algorithms to monitor broccoli plants, while Lin et al. (2023) applied UAV data for automated tobacco plant counting, achieving higher accuracy than traditional methods.

Specific crop traits, such as biomass, nitrogen uptake, and chlorophyll content, can also be effectively monitored using UAVs. Hütt et al. (2022) demonstrated the use of LiDAR-equipped UAVs to monitor biomass and nitrogen uptake in winter wheat. UAV hyperspectral imaging has been used to predict wheat leaf nitrogen content (Ma et al., 2022b) and chlorophyll content in potato crops (Yin et al., 2022), offering non-destructive methods for plant nutrition monitoring.

Weed detection and management are other areas where UAVs have shown considerable promise. UAVs can provide high-resolution imagery that allows for precise weed mapping and identification, as seen in studies by Wang et al. (2022) and Castellano et al. (2023). These capabilities are essential for precision agriculture, where targeted weed management can lead to more efficient use of herbicides and better crop yields.

UAVs have also been employed in early disease detection, a critical aspect of maintaining crop health. Bouguettaya et al. (2022) explored the use of UAVs combined with deep learning to identify plant diseases, offering a cost-effective and efficient solution. UAVs equipped with multispectral cameras have been used to detect coffee leaf rust at an early stage (Soares da Silva et al., 2022) and to classify plant diseases in real-time using advanced sensors like the NVIDIA Jetson Nano (Yağ and Altan, 2022). Additionally, UAVs have been utilized to detect Fusarium head blight in wheat using RGB sensors and advanced algorithms (Bao et al., 2024).

In the area of topographic mapping and irrigation management, UAVs offer high precision and adaptability. Du et al. (2022) developed a topographic mapping system for precision farmland leveling using UAVs equipped with LiDAR and PPK-GNSS, achieving centimeter-level accuracy. UAVs have also been employed to detect irrigation gaps in vineyards, helping to prevent water wastage (Sulemane et al., 2022), and to monitor crop moisture levels (Gao et al., 2023b; Peng et al., 2023).

The ability of UAVs to navigate complex terrains and provide data from areas difficult or impossible to reach with ground equipment further enhances their utility in precision agriculture (Akstinas et al., 2022; Xin et al., 2022; Sandino et al., 2023). This capability, combined with their cost-effectiveness and flexibility, makes UAVs invaluable tools for modern farming. Although satellites provide extensive coverage and frequent revisits, their limitations in spatial resolution and ground-level detail capture often make UAVs the preferred choice for detailed agricultural monitoring.

UAVs offer high-resolution, flexible, and timely data collection capabilities that significantly enhance precision agriculture practices. Their ability to integrate multiple data sources and operate in various terrains, coupled with real-time data analysis, positions them as essential tools for modern agricultural management. The integration of UAV and satellite data can provide a comprehensive approach, leveraging the strengths of both platforms to improve overall data quality and application in precision agriculture.

Existing frameworks using UAV data

Recent advancements in UAV technology have led to the development of various frameworks and models for precision agriculture and environmental monitoring. These frameworks leverage UAVs' capabilities to capture high-resolution data, offering innovative solutions for diverse applications.

Du et al. (2022) developed a topographic mapping system specifically designed for precision farmland leveling. This system integrates low-altitude

UAVs with LiDAR and PPK-GNSS, achieving centimeter-level accuracy. This technology enables efficient topographic surveys, providing crucial data for precision leveling in agriculture.

Haumont et al. (2022) introduced a model to predict leek dry biomass and nitrogen uptake using UAV-based multispectral imaging. The researchers tested various modeling approaches using 12 spectral vegetation indices (VIs) and their interquartile ranges as predictors. The best-performing models were a lasso regression model for dry biomass and a simple linear regression model based on the red wide dynamic range vegetation index (RWDRVI) for nitrogen uptake. However, the model's accuracy diminished with data from different growing seasons, suggesting a need for recalibration for consistent performance.

Kumar et al. (2022) presented a transformer-based encoder-decoder architecture for precise semantic segmentation of UAV images. This architecture incorporates a self-attention-based transformer in the encoder to capture global contextual information and a token spatial information fusion (TSIF) module to integrate local details. The resulting pixel-level semantic predictions demonstrated high accuracy in segmenting complex aerial scenes, validated on the UAVid and Urban Drone datasets.

Ma et al. (2022a) developed a model using a combination of a one-dimensional convolutional neural network (1D-CNN), random forest (RF), and support vector machine (SVM) to identify forest tree damage levels caused by Erannis jacobsoni Djak. These models were built using sensitive features extracted from UAV multispectral vegetation indices and texture features. Among the models, the 1D-CNN based on vegetation index-sensitive feature sets showed the highest accuracy. The study's results offer a practical reference for accurately identifying forest tree damage levels and managing forest pests.

In the domain of wildfire management, Muksimova et al. (2022) introduced a deep encoder-decoder network with a two-pathway architecture for real-time wildfire segmentation using UAV images. The advantages of UAVs in this context include their ability to capture images from different angles, cover large areas quickly, and provide high-resolution data, which is critical for accurate fire detection and segmentation.

Yağ and Altan (2022) developed a robust hybrid classification model using AI algorithms for real-time plant disease detection in agricultural environments. The model combines swarm optimization-supported feature selection with machine learning and deep learning algorithms to classify diseases in apple, grape, and tomato plants. This model is embedded in the NVIDIA Jetson Nano developer kit on a UAV, allowing real-time classification tests with high accuracy.

Zheng et al. (2022) utilized simple linear regression models and random forest regression algorithms to predict rice grain yield from UAV multispectral imagery. The random forest regression algorithm was particularly effective in handling nonlinear and hierarchical relationships among multiple variables, making it suitable for diverse datasets involving different years, cultivars, and climatic zones.

Agrillo et al. (2023) developed a model for detecting coastal dune habitats by combining very high-resolution UAV imagery with field survey data. This approach involved object-based image analysis (OBIA) and supervised machine learning classification using a random forest model. Conducted in a protected coastal ecosystem in Italy, the model achieved an overall accuracy of 78.6%, demonstrating the potential of UAV imagery for accurate and efficient habitat mapping in coastal areas.

Ma et al. (2023a) introduced a comprehensive growth monitoring indicator (CGMI) for summer maize based on UAV-collected multispectral remote sensing imagery. The CGMI integrates key growth indicators such as leaf area index (LAI), relative chlorophyll content (SPAD), and plant height (VH). The model utilizes partial least-squares regression (PLSR) and sparrow search optimization kernel extremum learning machine (SSA-KELM) algorithms to preict the CGMI, offering an efficient and non-destructive tool for monitoring maize growth.

Ma et al. (2023b) created the MultimodalNet model, which uses dynamic fusion of multimodal UAV imagery, including RGB, hyperspectral near-infrared (HNIR), and thermal imagery, for accurate field-scale yield prediction of winter wheat. The model's adaptive modality attention mechanism significantly improved yield prediction accuracy, particularly during the flowering stage, highlighting the importance of integrating HNIR and thermal imagery in yield prediction under different irrigation regimes.

Peng et al. (2023) created a framework for energy flux modeling using high-resolution thermal and multispectral UAV data to estimate canopy transpiration and soil evaporation accurately. This framework employs a two-source energy balance model, which provides detailed insights into the diurnal and seasonal dynamics of evapotranspiration, aiding in precise irrigation management and improving water use efficiency, particularly under drought conditions.

Ramachandran et al. (2023) developed a decision framework for selecting the most suitable survey strategy for characterizing microtopography in urban areas. This framework assesses the accuracy and elevation differences between UAV-based RGB data and aircraft LiDAR across various land use classes and flood features, ensuring the most effective characterization for flood management and risk assessment.

Lastly, Xie et al. (2024) introduced ResMANet, a deep-learning network designed for high-resolution remote sensing imagery. This network features a multiscale convolutional structure for extracting features at different scales, an attention mechanism for refining feature maps, and a joint loss function to address imbalanced data. The model was trained on a dataset created from UAV images and used to predict the invasion of Cassytha filiformis in the Xisha Islands, China.

While these frameworks and models advance UAV technology for precision agriculture and environmental monitoring, there are certain challenges and gaps identified. Integrating multiple sensor data types, such as RGB, HNIR, and thermal imagery, can increase complexity and cost. Moreover, models like the transformer-based encoder-decoder (Kumar et al., 2022) and ResMANet (Xie et al., 2024) require significant computational resources, limiting their practicality in field settings. There is a need to develop more efficient algorithms that maintain high accuracy while reducing computational demands. Additionally, some models are tailored to specific conditions or crops, limiting their scalability to other applications. Developing versatile and adaptable models for various agricultural and environmental contexts, especially for small-scale, irregular farms, remains a priority.

Justification of the use of RGB sensors over multispectral alternatives for small-scale rainfed agriculture

RGB sensors were chosen for this study due to their high spatial resolution, cost-effectiveness, and accessibility, making them suitable for small-scale farmers in resource-limited environments. While multispectral sensors require expensive near-infrared (NIR) bands to compute indices like the normalized difference vegetation index (NDVI), RGB sensors can still facilitate effective crop classification through alternative vegetation indices such as the visible atmospherically resistant index (VARI) and the triangular greenness index (TGI) (Gerardo & de Lima, 2023) or indices proposed by this study. Unlike multispectral sensors, which often have lower spatial resolution, RGB sensors provide high spatial resolution imaging (Digital Agriculture Laboratory, 2023). High-resolution UAV RGB imagery has been widely utilized for land cover classification (Gkillas et al., 2022; Li et al., 2022; Azizi et al., 2024) and advanced machine learning applications for crop monitoring, including disease detection (Bao et al., 2024; Liu et al., 2024; Wieme et al., 2024), yield prediction (Killeen et al., 2024; Qu et al., 2024; Zhang et al., 2024), and crop condition assessment (Feng et al., 2024; Tian et al., 2024). These studies demonstrated the effectiveness of using UAV RGB imagery alone without relying on multi-spectral, hyperspectral, or other complementary data sources. High spatial resolution imaging is particularly useful for assessing heterogeneous smallholder farms. The affordability and ease of deployment of RGB sensors make them a scalable solution for precision agriculture in semi-arid regions, where financial and technical constraints limit access to advanced remote sensing technologies (Cucho-Padin et al., 2019).

Proposed framework

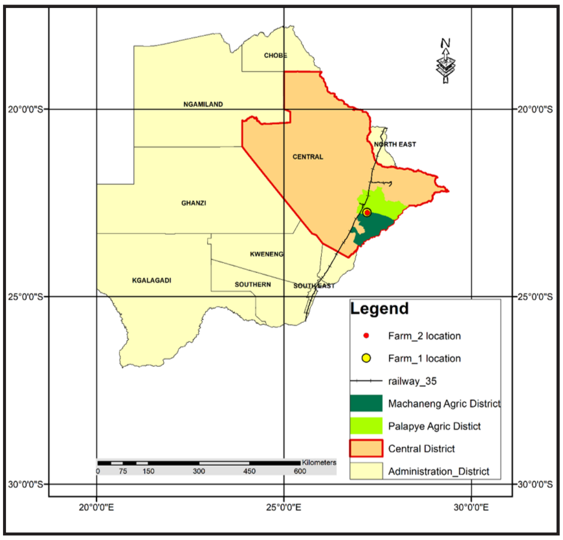
This research developed a precision crop farming framework (PCFF) for small-scale rainfed agriculture using UAV RGB high-resolution imagery to address several gaps identified in existing frameworks and models. Precision crop farming in this research is defined as the management of heterogeneous farm activities based on UAV imaging remote sensing systems integrated with global positioning and information systems. The research was carried out on small-scale subsistence farms under rainfed agriculture in semi-arid regions. The aim is to enhance farm management by providing precise spatial and temporal information in heterogeneous farming systems in Botswana's semi-arid regions. The framework was specifically designed for small-scale farming systems, where farmers practice heterogeneous planting and crop mixing on small plots of land. It provides agricultural land use planners with essential information about the location of farms, plowed areas, crops planted, and their growth patterns for informed decision-making. Additionally, it helps farmers understand the variabilities across their entire farms.

The study's aim to enhance farm management by providing precise spatial and temporal information in heterogeneous farming systems in Botswana's semi-arid regions aligns with the broader goal of reducing Botswana's reliance on food imports, thereby contributing to greater food security and self-sufficiency in the country (FAO, 2023).

Materials and methods

Description of the study area

The research was conducted in the agricultural districts of Palapye and Machaneng in Botswana, specifically focusing on the areas of Lecheng and Pilikwe (Figure 1). These locations were selected due to their traditional small-scale crop production practices under rainfed farming conditions. The geographical coordinates of the study area range from 27.091° to 27.097° East and from -22.640° to -22.855° South.



Source: Own elaboration based on publicly available information from Ministry of Agriculture of Botswana, 2018

Figure 1: Map showing the study area within the agricultural districts of Palapye and Machaneng.

The soil types in this area include arenosols, leptosols, and luvisols, each with distinct characteristics that influence agricultural productivity (IUSS Working Group, 2015; Sileshi et al., 2022). Arenosols, characterized by sandy texture, have low resilience to erosion and poor water and nutrient retention, limiting crop performance in arid and semi-arid regions. Despite these challenges, arenosols are easy to cultivate and suitable for root and tuber crops. Leptosols, which are shallow and coarse-textured, are prone to erosion and require careful management to support sustainable crop growth. In contrast, luvisols are fertile soils with high-activity clays and high base saturation, making them suitable for a wide range of agricultural uses. These soils contribute to the varied agricultural potential of the study area, necessitating tailored management practices to optimize crop production.

The vegetation covering the area predominantly consists of mopane (Colophospermum mopane) and acacia species. Sorghum is the most popular grain crop, followed by maize and millet. Other crops grown in the area include melons, pulses, and beans. The agricultural practices are primarily focused on subsistence farming, with an emphasis on rainfed crops.

Research design

The research design adopted a mixed-methods approach, combining both quantitative and qualitative methods to achieve the study's objective. This approach allowed for a comprehensive analysis of the data collected, ensuring that the research questions were thoroughly addressed (Cresswell and Cresswell, 2022; Yin, 2018).

The study employed a combination of observational and experimental designs. The data collection process using UAV imagery followed an observational design, wherein agricultural conditions were observed and recorded without manipulation of variables. In the subsequent stages, particularly when developing and applying machine learning algorithms to the UAV imagery, the study transitioned to an experimental design. This dual approach facilitated a robust analysis of the data, allowing for both descriptive and inferential insights.

UAVs equipped with RGB cameras and GNSS were used to capture high-resolution images of farmland at various heights, ensuring accurate geo-referencing with ground control points (GCPs). The data underwent preprocessing steps like orthorectification and mosaicking to create seamless images.

Critical thinking was a core component of the research design, guiding the linkage and analysis of the PCFF components (Paul and Elder, 2006; Heard et al., 2020). This process involved incorporating both the collected data and external data sources to ensure a comprehensive and well-rounded analysis. Four systematic steps were followed: (1) selecting spatial data collection platforms, (2) defining UAV-based data acquisition methods, (3) processing data using spatial analysis tools and new vegetation indices, and (4) presenting the framework to diverse user groups through publications and conferences. Machine learning algorithms, ISODATA and SVM, were developed and applied for data classification, achieving high accuracies. The framework was validated through statistical methods, as follows: (1) confusion matrices, (2) cross-validation using inverse distance weighting (IDW), mean absolute error (MAE) and root mean squared error (RMSE), and (3) t-tests (Bolo et al., 2024).

Methods for spatial data collection

The spatial data for this study was collected using a combination of UAV and GNSS systems, providing a comprehensive dataset for subsequent analysis. Ground control points were gathered using a GNSS receiver handheld instrument and stored as point vector data. UAVs were used to collect spatial data on plowed areas and crops (raster data). This data was subsequently stored in a computer system for processing and analysis, transforming it into geospatial information accessible for decision-making purposes. GNSS position data (latitudes and longitudes) was employed to geo-reference the UAV data, ensuring accurate alignment and integration of spatial information.

The UAV data was captured with a passive sensor using manual flying control. The UAV used in this study was a DJI Phantom 4 quadcopter, equipped with a gimbal-stabilized imaging system allowing pitch adjustments from -90° to +30°. This UAV was chosen for its high-resolution imaging capabilities and inbuilt GPS and GNSS systems, which provided near-real-time data with high positioning accuracy.

The UAV had a normal airspeed of 20 m/s, a maximum flight duration of 28 minutes, and a payload capacity of 1380 g. It featured an RGB camera with a spectral sensor range of 0.45 to 0.69 micrometers (µm). An RGB sensor was preferred over multispectral sensors because it provided clear views of agricultural fields, allowing for easy counting of plants. The camera had a focal length of 4 mm, which was used to calculate the spatial resolution of the captured data. The captured data had a pixel resolution width and height of 4000 and 3000 pixels, respectively, resulting in a maximum image size of 4000 x 3000 pixels. The swath width was 2.4 m at a height of 120 m, 1 m at a height of 50 m, and 0.2 m at a height of 5 m. The UAV collected data on farm activities, including plowed areas and crops. The spatial resolution of the collected data was 0.19 cm per pixel at 5 m, 1.93 cm per pixel at 50 m, and 4.63 cm per pixel at 120 m.

The UAV was operated under controlled conditions to capture high-resolution images of the farmland at various heights, ensuring accurate geo-referencing with ground control points (GCPs). The data underwent several preprocessing steps, including orthorectification and mosaicking, to create seamless images that accurately represented the study area. An 80% forward and backward overlap was adopted during data collection to minimize edge distortions. Different flight heights were utilized − 120 meters to view the entire farm, 50 meters to identify crop types, and 5 meters to assess crop conditions. These heights were selected based on experimental observations, to capture detailed and accurate data on farm boundaries, crop types, and planting patterns. The spatial resolution was calculated based on the flight height (H), sensor height (H_s), focal length (f), sensor width (W_s), and image width (W_i) using the following formulas:

$$GSD_h = \frac{H \cdot H_s}{f \cdot H_i}, \quad (1)$$

$$GSD_w = \frac{H \cdot W_s}{f \cdot W_i}, \quad (2)$$

where GSD_h and GSD_w are the round spatial distance height and width, respectively.

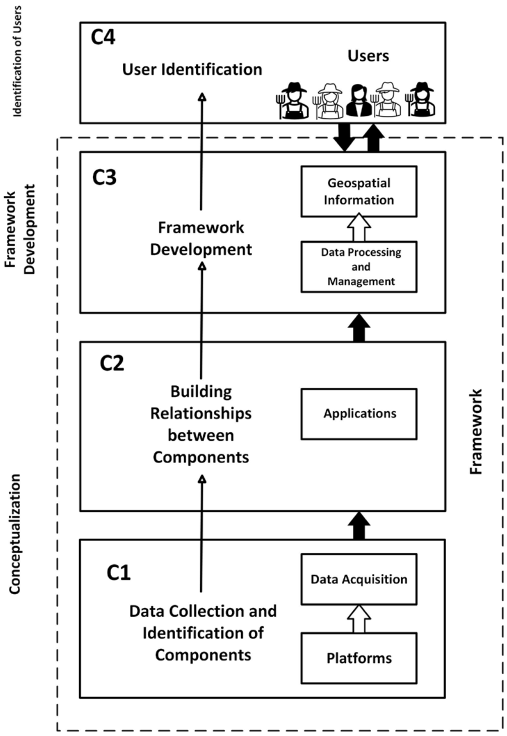
The UAV data provided a comprehensive view of the farm activities, including plowed areas and crop conditions, essential for building the PCFF.

Methods for building a precision crop farming framework (PCFF) for small-scale rainfed agriculture using UAV RGB high-resolution imagery

The development of the PCFF was guided by a critical thinking analysis approach, which involved evaluating the linkages between the various components of the framework (Paul and Elder, 2006; Heard et al., 2020). This approach was essential in ensuring that the framework was not only theoretically sound but also practically applicable in the context of small-scale rainfed agriculture. During this process, external information was also considered rather than relying solely on the collected data. Information on data collection methods, including airborne (aircraft) and satellite imaging systems, was considered for comparison. Before reaching conclusions, alternative possibilities, such as changing the sensor height to collect images with better spatial resolution, were also evaluated to ensure well-reasoned outcomes.

In this study, data and component analysis, as well as their linkages, were conducted continuously, both during and after data collection. The analysis aimed to evaluate the data and link it with the framework components. An inductive and descriptive analysis method was used to trace these relationships, which were essential to the framework. The relationships between components were described and explained as part of the framework.

Four steps were taken to develop a precision crop farming framework (PCFF) for small-scale rainfed agriculture using UAV RGB high-resolution imagery as illustrated in Figure 2.



Source: Own elaboration, 2024

Figure 2: The PCFF development structure.

The first step, linked to Component C1, involved selecting the platforms to be used for spatial data collection. An extensive literature review was conducted to identify platforms capable of providing high-resolution spatial and temporal data. UAVs were identified as the primary platform for this purpose, offering the flexibility to collect data anytime and anywhere. The Global Navigation Satellite System (GNSS) was chosen as a crucial platform for providing accurate location and navigation data.

The second step, related to Component C2, focused on the data acquisition approach, specifically how the UAV platform captured spatial data. The UAV was applied to manage various crop farm activities, including crop cover assessment, planting methods, area coverage, and crop variability across the entire field. The components identified in the first step were linked together to establish relationships between variables, using a critical thinking analysis approach. This step also involved optimizing the data acquisition process by considering alternative methods, such as adjusting sensor heights and employing different UAV flight patterns, to enhance the quality and accuracy of the collected data.

The third step, associated with Component C3, involved processing and managing the collected spatial data using various tools and techniques. This included the development of new vegetation indices − visible green vegetation index (VGVI) and only visible green vegetation index (OVGVI). VGVI and OVGVI were introduced in this study to address limitations in vegetation monitoring using RGB imagery, particularly for small-scale rainfed agriculture. These indices were designed to utilize only the visible spectrum, making them suitable for UAV-based precision agriculture applications (Bolo et al., 2024). These indices were calculated using the following formulas:

$$VGVI = \frac{G - R}{2G + R}, \tag{3}$$

$$OVGVI = \frac{(G - R)}{(G + R)} \div (G + R), \tag{4}$$

where G is green band reflectance, and R is red band reflectance.

Additionally, machine learning algorithms such as ISODATA and SVM were applied for data classification. These tools and techniques were integral to producing agricultural spatial information, such as crop cover and health status. The data processing also involved the use of advanced spatial analysis software, which allowed for the integration of multiple data sources and the generation of detailed maps and models representing the agricultural landscape.

The final step was to identify the framework users (Component C4). This was accomplished by presenting the framework to stakeholders in various sectors through journal publications, international conferences, and national agricultural shows. By engaging with a broad audience, the framework was positioned for widespread adoption and application. The identification of user groups also involved gathering feedback from potential users, which was used to refine and improve the framework, ensuring its relevance and usability in real-world agricultural settings.

By employing critical thinking throughout these steps, the research produced a precision crop farming framework for small-scale rainfed agriculture using UAV RGB high-resolution imagery.

Validation of data processing models using statistical methods

The validation of the PCFF was a critical aspect of the research, ensuring that the framework was both accurate and reliable. The validation process involved several steps, each designed to assess different aspects of the framework's performance.

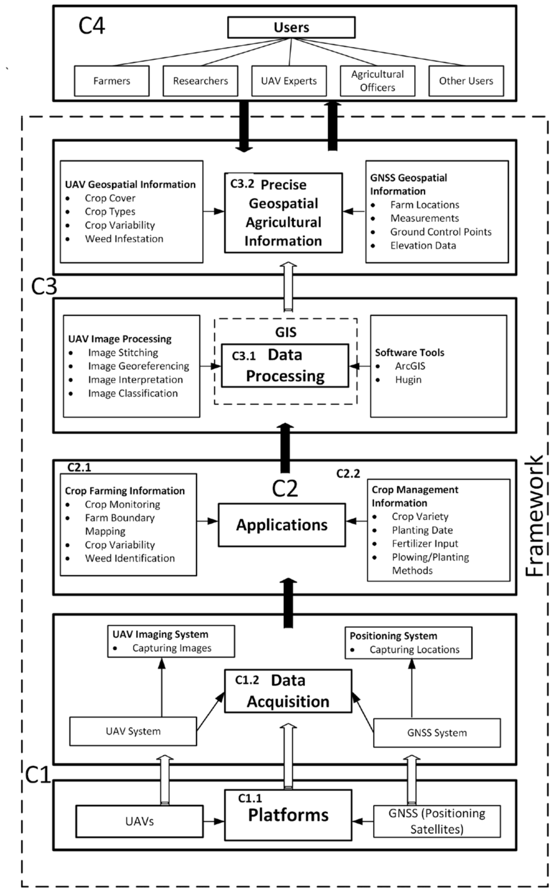
Data collected during the study was processed and transformed into geospatial information, providing insights into farm layout, land use, and cover. The performance of the ISODATA and SVM data processing models was evaluated using statistical methods, including correlation matrices, confusion matrices, and t-tests. These methods provided a comprehensive assessment of the models' accuracy, including omission and commission errors, producer's and user's accuracy, and overall accuracy.

Confusion matrices were employed to evaluate the classification performance of the ISODATA and SVM models, comparing the predicted classes against the ground truth data. The results were expressed in terms of accuracy, precision, recall, and F1-score, providing a detailed understanding of the strengths and weaknesses of each model. Additionally, cross-validation techniques were used to assess the robustness of the models, ensuring that they performed consistently across different subsets of the data (Bolo et al., 2024).

The results of these evaluations indicated no statistically significant difference between the performance of the ISODATA and SVM models, suggesting that both could be used effectively, depending on the specific requirements of the application and available computational resources. This finding was further supported by the t-test results, which confirmed the models' equivalence in terms of classification accuracy.

Results and discussion

This study developed a precision crop farming framework (PCFF) tailored for small-scale rainfed agriculture in Botswana, leveraging UAV RGB high-resolution imagery as the primary data source. The framework, as illustrated in Figure 3, serves as a user-friendly system designed for efficient crop management by integrating UAV RGB imagery with GNSS data. The PCFF comprises four main components: the data collection component (C1), the applications component (C2), the analysis and results component (C3), and the users component (C4).



Source: Own elaboration, 2024

Figure 3: Precision crop farming framework (PCFF) for small--scale rainfed agriculture using UAV RGB high-resolution imagery.

Each of these components plays a critical role in transforming raw spatial data into actionable geospatial information, ultimately supporting decision-making processes in precision crop farming.

The data collection component (C1)

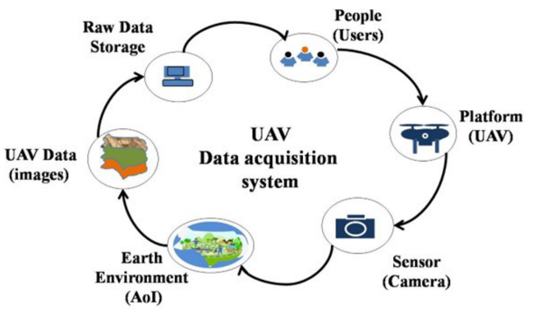
The first component, C1, initiates the data pipeline by collecting high-quality spatial data essential for precision farming. This component is subdivided into two key subcomponents: *platforms* (C1.1) and *data acquisition* (C1.2).

Platforms subcomponent (C1.1)

Platforms within the PCFF refer to the devices and instruments responsible for capturing spatial data and ensuring its precision. In this study, two primary platforms were utilized, namely UAVs and GNSS receivers. The UAVs used were equipped with high-resolution RGB cameras capable of capturing detailed imagery of farm activities. These UAVs also featured integrated signal receivers compatible with both GPS and GNSS systems, enabling accurate spatial referencing of the captured images. The GNSS receiver played a crucial role in collecting location data by providing accurate geospatial coordinates that were essential for mapping farm boundaries, crop zones, and GCPs.

Data acquisition subcomponent (C1.2)

The data acquisition subcomponent, C1.2, is responsible for capturing, processing, and storing the spatial data. The UAV data acquisition system within this framework is composed of six elements, as demonstrated in Figure 4: users, UAV platforms, sensors (cameras), agricultural environment (area of interest), UAV imagery data, and data storage.



Source: Own elaboration, 2024

Figure 4: The UAV data acquisition system where AoI is an area of interest.

The users in this context include farmers, decision-makers, and researchers who operate the UAVs to collect imagery data. The UAV platform, carrying sensors, flies over the agricultural environment (the area of interest) to capture detailed images of ground features such as plowed areas, crop types, and crop health. These images are then stored and processed to generate geospatial information that is critical for planning and decision-making. This subcomponent ensures that the data captured is precise, timely, and relevant to the needs of the end users.

The applications component (C2)

The second component of the PCFF, C2, focuses on the application of UAV imagery in managing crop farming activities through the generation of geospatial agricultural information. C2 is divided into two subcomponents: crop farming information (C2.1) and crop management information (C2.2).

Crop farming information (C2.1)

Crop farming information refers to the data and insights derived from UAV imagery that are directly related to the cultivation and management of crops. This study achieved a remarkably high spatial resolution of 0.19 cm/pixel, which enabled the precise identification of individual crops from the captured images. Such high resolution is essential for monitoring crop health, identifying areas with pest infestations or nutrient deficiencies, and assessing the effectiveness of farming practices.

The UAV systems employed in this study provided farmers with the ability to monitor their fields in real time, identifying areas that required specific attention. For instance, through the analysis of UAV imagery, farmers could determine which areas needed irrigation, fertilizer application, or pest control, thereby optimizing resource use and improving crop yields.

Crop management information (C2.2)

Crop management information encompasses the broader aspects of farm management that benefit from the geospatial data captured by UAVs. This includes the planning of planting schedules, selection of crop varieties, and implementation of precision farming techniques. The UAV imagery was used to generate detailed maps showing crop cover, field boundaries, and variability within the fields. These maps were instrumental in guiding farmers on where to plant specific crops, how to optimize field layouts, and how to manage different areas of the farm based on soil and crop conditions.

Moreover, the study introduced new vegetation indices derived from UAV RGB imagery, such as the visible green vegetation index (VGVI) and the only visible green vegetation index (OVGVI) (Bolo et al., 2024). These indices were calculated using Equations (3) and (4). NDVI, first introduced by Rouse et al. (1974) as a measure of plant health, is still widely utilized for various applications (Ma et al., 2022a, 2022b, Soares da Silva et al. 2022; Ma et al., 2023a, 2023b; Mndela et al., 2023; Sandino et al., 2023; Ferro et al., 2024; Kodl et al., 2024). However, NDVI relies on HNIR, and, therefore, requires expensive multispectral sensors, making it less accessible for small-scale farmers. In contrast, VGVI and OVGVI utilize only RGB bands from UAV imagery, providing a cost-effective alternative for assessing vegetation in resource-limited settings. While NDVI offers a broader measure of vegetation health, VGVI and OVGVI effectively distinguish green vegetation from non-vegetation areas, particularly in rainfed agricultural environments. The study validated these indices using high-resolution UAV images, demonstrating their ability to provide detailed spatial differentiation of crops and land cover, making them highly suitable for precision agriculture.

These indices were crucial in distinguishing vegetated areas from non-vegetated ones, particularly in the semi-arid regions of Botswana where drought conditions and soil fertility issues are prevalent. This would help identify areas that required intervention, such as replanting or soil amendment, to ensure optimal crop growth.

The analysis and results component (C3)

The third component of the PCFF, C3, is where the data collected from components C1 and C2 is managed, analyzed, and transformed into useful geospatial information. This component consists of two subcomponents: data processing and geographical information systems (GIS) (C3.1), and geospatial information (C3.2).

Data processing and GIS (C3.1)

The data processing subcomponent involves the transformation of raw UAV imagery and GNSS data into actionable geospatial information. The study employed various image processing techniques such as image stitching, enhancement, geo-referencing, and classification to convert the raw data into geospatial formats. The UAV RGB images were stitched together to form continuous, high-resolution images of the entire farm, which were then geo-referenced using ground control points collected by the GNSS receiver. This process ensured that the imagery was accurately aligned with real-world coordinates, allowing for precise mapping and analysis.

The study also utilized classification algorithms like ISODATA and SVM to analyze the UAV RGB images. These algorithms were employed to classify different crop types and assess crop cover across the fields. The ISODATA algorithm, in particular, showed superior performance with an accuracy of 82.5% and a kappa coefficient of 0.825, indicating a high level of agreement between the classified images and the ground truth data. The SVM algorithm, while slightly less accurate with an 81.1% accuracy and a kappa coefficient of 0.688, was still effective in distinguishing between different crop types, particularly in areas with mixed vegetation (Bolo et al., 2024).

Geospatial information (C3.2)

Geospatial information refers to the final output of the data processing activities, presented in the form of digital maps, charts, and databases. These outputs are crucial for decision-making in precision crop farming. The study produced various types of geospatial information, including vector maps showing farm boundaries, crop zones, and areas of interest, as well as raster images displaying crop cover and variability across the fields.

The digital maps generated from the processed data were used to visualize the spatial distribution of different crops and to assess the variability in crop health and soil conditions across the farms. For example, the study created detailed maps of two farms, showing the exact locations of different crop types, the extent of plowed areas, and the variability in crop cover. These maps provided farmers with a clear understanding of their fields, enabling them to make informed decisions about planting, irrigation, and fertilization.

Additionally, the study introduced new geospatial information products, such as the rasterized UAV RGB images and the vectorized farm activity maps. These products would allow farmers to monitor their fields more effectively and to plan their farming activities with greater precision.

The users component (C4)

The fourth component of the PCFF, C4, represents the users of the framework. This component is divided into internal and external users, each playing a distinct role in the operation and utilization of the framework.

Internal users

Internal users are those directly involved in the operation of the UAVs and the processing of the data. This group includes UAV experts, GNSS operators, and data analysts who are responsible for capturing, processing, and analyzing the spatial data. These users ensure that the data collected is accurate and that the geospatial information produced is reliable and useful for decision-making.

External users

External users are the end-users of the geospatial information generated by the PCFF. This group includes farmers, agricultural extension workers, researchers, and other stakeholders such as students and young farmers. The external users rely on the information provided by the framework to make informed decisions about their farming activities. For instance, farmers might use geospatial information to determine where to plant specific crops, how to manage their fields, and when to apply fertilizers or pesticides.

Results of the framework validation

The study validated the framework by applying it to two farms and assessing the accuracy of the geospatial information produced. The results of the validation showed the effectiveness of PCFF in capturing and processing spatial data, producing accurate and detailed geospatial information that could be used for precision crop farming.

Validation of the UAV data collection process and image processing techniques

The UAV data collection process was validated by comparing the captured images with ground truth data. The UAV used in the study, a DJI Phantom 4, captured high-resolution RGB imagery at various flight heights, ranging from 5 meters to 120 meters. The images were then processed to produce detailed maps of the farms, showing crop cover, field boundaries, and variability in crop health.

The image processing techniques used in the study, including image stitching, geo-referencing, and classification, were validated by comparing the processed images with the ground truth data. The results showed that the image processing techniques were highly effective, producing accurate geospatial information with minimal errors.

Validation of geospatial information products

The geospatial information products generated by the framework, including digital maps and classified images, were validated by comparing them with existing geospatial data and related work in the field. The results showed that the PCFF produced geospatial information with high accuracy, with extraction precision and kappa coefficients comparable to or better than those reported in related studies.

For instance, the study's use of UAV RGB imagery for generating geospatial information on land use and crop cover achieved accuracies of 83% to 94%, with kappa coefficients indicating strong agreement with the ground truth data. These results validate the effectiveness of the PCFF in producing reliable geospatial information that can be used for precision crop farming.

Conclusion

This study presents a precision crop farming framework (PCFF) tailored for small-scale rainfed agriculture, utilizing UAV RGB high-resolution imagery to enhance farm management and productivity. The mmain contributions of this research include the development of a user-friendly framework that integrates UAV and GNSS data for precise spatial and temporal farm monitoring. By focusing on small-scale, heterogeneous farming systems, the PCFF addresses the specific needs of farmers in semi-arid regions, providing actionable insights into crop conditions, planting patterns, and farm variabilities.

However, our research has several limitations. The reliance on RGB sensors, while cost-effective and suitable for resource-limited settings, limits the ability to capture detailed spectral data available from multispectral or hyperspectral sensors. In addition to that, the framework's applicability to other contexts may be constrained by its design, which is tailored specifically for semi-arid, small-scale farming systems.

To address these limitations and expand the PCFF's applicability, the following areas are suggested for future research. The incorporation of multispectral and/or hyperspectral sensors would allow researchers to capture a broader range of data for more detailed crop and land use analysis. Machine learning algorithms other than ISODATA and SVM should be implemented and tested to establish whether they could reduce computational load while maintaining high accuracy. Further studies should also be conducted to adapt and test the framework in different agricultural contexts and regions (i.e., other Southern African countries) to enhance its versatility and applicability.

Acknowledgments

The authors declare that they have not received any funding to support this publication. The authors declare that they have no conflict of interest.

The contributions of each author are as follows. Ms. Basuti Bolo is a PhD student at Botswana International University of Science and Technology, Botswana. This paper is based on her PhD research.

She was responsible for the primary research, data collection, analysis, and initial drafting of the manuscript. Prof. Irina Zlotnikova is a co-supervisor of Ms. Bolo. She participated in the writing and revision of the manuscript, prepared the review of the most recent relevant publications, and produced visual materials (Figures 2 and 3). Dr. Dimane Mpoeleng, as the principal supervisor of Ms. Bolo, provided the initial idea for this research, helped conceptualize the study, and participated in the revision and correction of the manuscript.

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Volume XVII Number 1, 2025

Drivers of Credit Supply in Iran's Agriculture: Symmetric or Asymmetric Relationship?

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Abstract

Agriculture, one of the most important sectors of the Iranian economy that plays a vital role in providing food security and job opportunities, has always been faced with a lack of financial and credit resources. Therefore, identifying the drivers of credit supply to this sector is of great importance. The main objective of this study was to determine the factors affecting Agriculture Bank (Bank Keshavarzi of Iran) credit supply as the main source for financing agricultural activities, in Iran. In this regard, provincial panel data for period 2007-2020 and non-linear autoregressive distributed lag model, which distinguishes this research from those of previous years, have been used. The results indicate the asymmetric effect of all independent variables on credit supply of Agricultural Bank or the superiority of non-linear model in explaining the relationship between variables. For example, the positive shock on the value of bank assets with coefficient of 0.18 and its negative shock with coefficient of -0.05 will affect the growth of credit supply in the long run.

Based on research findings and in order to increase credit supply, it is recommended that Agricultural Bank put the control of non-current receivable more effectively (especially through careful evaluation of borrowers' eligibility) in its policy priorities and, therefore, reduce credit risk and perform more effective services in financing of agricultural sector. In addition, an increase in the bank's assets through investment in modern information and communication technologies is strongly recommended.

Keywords

Non-current receivable, NARDL, Agricultural Bank, Iran.

Feizizad, F., Nessabian, S. and Moghaddasi, R. (2025) "Drivers of Credit Supply in Iran's Agriculture: Symmetric or Asymmetric Relationship?", *AGRIS on-line Papers in Economics and Informatics*, Vol. 17, No. 1, pp. 21-30. ISSN 1804-1930. DOI 10.7160/aol.2025.170102.

Introduction

Banks are considered as the most important sources for financing enterprises, production, and investment projects in developing and developed countries (Banga, 2013). In fact, banks are linked to the real economic sector through the monetary policies implemented by the central bank. These policies are discussed from both supply and demand perspectives. The monetary view (demand side) that is analyzed through the interest rate channel and exchange rate, and the credit view (supply side) can be assessed through the provided facilities and the banks' balance sheet (Mishkin, 2013).

In this regard, present research focuses on supply side. All economic strata of a country, especially households, businesses, and manufacturing as well as government are involved with banks and banking facilities because it is a requirement of a dynamic economy. Banks are therefore the main source of financing for firms in many countries of the world. Access to banking facilities and credits for many firms provides the opportunity to invest in projects and the economic development. Banks are therefore highly effective in the economic development of countries and improve the economic growth of countries.

From an economic point of view, access to credit and other banking services is very important for economic agents (households, businesses and government). Bank credits are a useful tool for promoting economic growth, especially in the early stages of development. This stems from the basic importance of credit in providing the necessary funding for investment projects in developing countries since bank deposits are the most important part of the national money supply. Thus, a large portion of the capital needed by the production units is provided by the banking system.

Thus, the performance of banking system is vital in production, economic prosperity and prices of goods. Uncertainty in access to bank credits and its associated cost provides a good ground for economic disarray. Therefore, identifying factors influencing credit supply can contribute significantly not only to the growth and development of banks but also to the development of the country. Thus, present study focuses on exploration of credit supply drivers of Iran's Agricultural Bank (IAB) using provincial panel data.

In Iran, various institutions and institutions, both official and informal, are responsible for financing the agricultural sector, including commercial banks, agricultural banks, rural co-operative organizations, agricultural sector support funds, nomadic co-operatives, Al-Hasana loan funds, unions and production cooperatives, and other producers' organizations from official and unofficial sources of financing of the agricultural sector. However, the most important institution among the above mentioned issues has been the Agricultural Bank.

Bank credits for agricultural sector are provided at both macro and micro levels. Since most of the poor are in rural areas, and most of them are involved in agriculture and related activities, the amount allocated to this sector is usually at micro level, and this solution (micro credit to agriculture sector) has always been regarded as an appropriate way to reduce poverty. In rural and agricultural development, one of the most important ways to solve the financial problems of farmers is to give facilities at the micro level, which plays a significant role in focusing and directing the low-level rural capital and creating a spirit of participation and also expanding public activities (Hacievliyagil and Eksi, 2019).

On the other hand, farmers seek bank credits to supply machinery such as tractors, raw materials such as fertilizers and farmland, and to provide the necessary facilities to improve the agricultural sector performance, as well as purchasing and paying the equipment costs to raw materials. Bank credits are therefore of considerable importance in the agricultural sector, and in many developing countries credit financing is the most important financial tool in large-scale private savings (Awad and Al Karaki, 2019).

In general, the goals and areas for which micro-credits are allocated in the agricultural sector are: -1 credit for meeting individual needs such as preparing pesticides for agricultural pests, purchasing chemical fertilizers, purchasing agricultural inputs, repairs to agricultural equipment such as tractors and water pumps. 2- Short-term assistance to farmers to solve liquidity problems, due to the seasonal nature of the crop and farmers' income. 3- Helping the farmers to meet their need and avoid going to the informal financial sector and ease of obtaining loans and credits from official credit sources due to lack of collateral (Bakhtiari and Shayesteh, 2006).

Factors affecting the supply of facilities in both supply and demand dimensions are studied. The present study focuses on the supply dimension. In this context, factors affecting the granting of facilities in the supply side focus on factors affecting the volume of facilities granted by banks. These factors are common in the three main categories of domestic factors of banks and balance sheets, macroeconomic factors and monetary policy factors (Rabab'ah, 2015).

There are many factors in the balance sheet and internal factors of banks. Bank size is one of the most important variables in domestic factors and bank balance sheet (Almazari, 2014). In this study, it is considered as an external variable to investigate factors affecting agricultural bank facilities in Iranian provinces. Bank size is defined as the ratio of bank assets (in this study by the Agricultural Bank) to total assets of the banking system in each province (Chernykh and Theodossiou, 2011). In addition, one of the most important problems of Iranian banking system is that bank facilities are highly efficient. Rising volume of current receivables (deferred receivables) has led to a serious challenge for bank liquidity management. On the other hand, accumulation of bank failures may pressure the central bank to supply liquidity with monetary base. Many factors increase non-current demand in the banking system, such as the continued devaluation of the national currency and the sovereign structures in companies and banks, severe fluctuations in forecasting markets, high dissimilarity of interest rates with common market rates, rising false jobs and employment of unqualified people in the export and import manufacturing industry have often used various banking facilities. One of the most important consequences of monetary activities of banks and credit institutions is loose monetary demand which has a significant impact on the economic performance of society. Non-current demands have many ramifications on the economy of a society, which can lead to even a recession if it is not properly monitored. Thus, non-current demands can, besides reducing banks' profitability, slow the flow of liquidity in an economy, lack of allocation of credit at the appropriate time and in a timely manner to apply productive investments in various fields of agriculture, trade and industry. non-current receivable are one of the most important factors influencing the granting of facilities in any banking system, which, if not taken seriously, can even have inadequate consequences on a society's economy such as the disruption of bank intermediation, increased credit risk and reduced economic growth (Imran and Nishat, 2013; Norozi et al., 2021).

On the other hand, there are important macroeconomic factors that can lead to large economic changes in financial markets, especially banks. The most important of these factors are the growth of the gross domestic product and the growth of the consumer price index of goods and services or the inflation rate. Therefore, in this study GDP growth and provincial inflation were used as the most important factors of supply of banking facilities in the macroeconomic sector (Sharma, P. and Gounder, 2012; Cucinelli, 2013; Rabab'ah, 2015; Rachman et al., 2018; Ahmed et al., 2021).

Another important factor influencing the supply of payment facilities is the monetary policy of the Central Bank. In this regard, one of the most important factors directly determined by the central bank of different countries is the interest rate of banking facilities. The interest rate of bank facilities is one of the most common tools of monetary policy (Arbabian et al., 2020). Interest rate is an important monetary policy tool to investigate factors affecting agricultural bank facilities in Iran's provinces. In accordance with the studies on interest rate as a factors determining granting policies also regarding the literature of interest rate studies about factors determining the granting of facilities, this study used the interest rate parameter as an important monetary policy tool.

In the following, the most important related studies that have been done in Iran and abroad are stated in order.

Taghavi and Lotfi (2006) investigated the effect of monetary policy on loans, liquidity and the volume of deposits in the banking system in the country during the years 1995-2003. The results showed that the monetary policy index in this study which has the legal deposit rate has a negative but very little effect on the growth of bank deposits and lending facilities. In other words, reducing the rate of legal deposit will increase the amount of deposits and facilities granted by banks.

Olivero et al (2011) investigated the link between macroeconomic uncertainty and lending in Ukrainian banks. The results indicate that there is a negative relationship between macroeconomic uncertainty (consumer inflation, producer and money supply uncertainty) and the ratio of bank loans to capital parameter. In this way, banks increase their lending ratios when macroeconomic uncertainty decreases. The banks' reactions to changes caused by uncertainty are not the same, and depend on the properties of banks such as size, profitability. Smaller banks are less able to change their behavior in response to changes in monetary policy. Moreover, monetary policy uncertainty is more affecting profitable banks due to their lending behavior.

Tari et al (2012) in a paper analyzes the relationship between real-sector production and lending behavior of Turkish commercial banks in asymmetric information conditions. This study investigates the dynamic relationship between bank credit facilities and nominal interest rate, volume of non-current materials, and difference in interest rate of loan with deposit interest rate, inflation rate and industrial production index. The results of their study indicate that the rate of inflation and interest rate vary with the interest rate of the loan and the specific level of interest rate are effective on loans offered by banks. Non-current demands are affected by nominal interest rates, but do not directly affect bank lending behavior. The facilities granted by banks also affect the real sector's production.

Brei and Schclarek (2013) analyzed the amount of lending in private and state banks during financial shocks in 50 countries between 1994 and 2009. The results of this study showed that the rate of bank loan supply in government banks is higher than that of private banks during the financial crisis due to the increase in liquidity.

Said (2013) investigated the dynamics of the supply channel of bank facilities in Malaysia during the period from 1999 to 2007, using data from the Panly 23 Bank of Malaysia. The results of his study showed that monetary policy has important effects on the average rate of bank lending in the country; The Malaysian banks have the ability to set their prices in the mortgage supply, as they are affected by market rate changes and policy rates. The results of his study also show that the increase in the risk leads to an expansion in the stock bond and loan supply. This leads to a strong correlation with the average mortgage rate.

Amini Asl (2014) in a study using the Co-integration and ARDL and 1971-2011 period data, investigated factors such as economic instability on the supply of facilities in Iran. He found that economic instability had an adverse effect on the granting of facilities to government banks in the long run. Moreover, granting of government facilities in Iran has a direct relationship with a deposit-to-asset ratio in the long run but there was no significant relationship in the short run.

Rabab'ah (2015) reviewed factors affecting the granting of facilities to commercial banks in Jordan. In this study, using data from 2005-2013 and data panel co-integration method and various factors of extravasation, domestic variables of banks, monetary policy and macro economy, the percentage of deposits, lending interest rate, the interest rate of deposits, the rate of legal reserves and the rate of inflation have no significant relationship with the granting of facilities in this country, but non-current loans to total loans and significant negative effect on liquidity and economic growth and the size of banks and the positive effect of lending and the rate of facilities in Jordan.

Shahchera and Taheri (2016) investigated the Monetary Policy Transition Mechanism for Bank Lending of Iran for 18 banks in the country for the period 2006-2013, using panel data. The results indicate that the base variables of capital and liquidity and bank size have a significant effect on the lending rate of Iran's banking network. Moreover, these effects increase with the use of monetary policy. In fact, the traditional bank loan channel and the bank's investment channel for the Iranian banking network were approved, although its impact was limited.

Zamanian and Ohadi (2016) In a study, factors affecting the allocation of credits to agricultural activities in Sirjan city were investigated. In this study, through collecting questionnaire data and reviewing customer records from 2010 to 2013 and probit econometric method, we found that variables such as age, education, value of property and monthly income of applicant have inverse relationship with bank credits and gender variable and have a direct and significant relationship with the lack of possibility of repayment of bank credits.

Mehrar and Khodadad (2017) in the study of the effects of macroeconomic fluctuations on lending behavior of Iranian commercial banks during the period 1974-2015 using the Autoregressive Econometric Model with Distributive Interruption (ARDL) showed that lending of commercial banks (loan to bank assets ratio) is related to output fluctuations during long-term trading periods. It is also associated with increased financial assets of commercial banks. The monetary base is also unable to increase bank lending ability (in terms of the loan-to-asset ratio), and in the long run it will decrease even a small amount.

Sanfilippo-Azofra et al (2018) in a study assessed the relationship between banking facilities and financial development in banks of 31 developing countries for 2000-2012 using the GMM method. Their study showed that countries suffering from system weakness, the process of lending in those countries is not affected by monetary policies. However, in developing countries with a sound financial system, lending in their banks is affected by monetary policy.

Alalaya & Ahmad (2020) assessed factors affecting the performance of 21 banks from commercial banks in Jordan using data from 2008 to 2018 and panel data method. The variables they selected to describe the performance of banks in the country such as unemployment ratio, GDP per capita, inflation rate, interest rate, capital efficiency, liquidity and bank size explained 64% of the performance of banks on average.

Arbabian et al (2020) investigated the impact of monetary sector development on the supply of financial facilities to private, public and Article 44 banks. Using the seemingly unrelated equation system (SUR) and the data from the 2011-2017 period, they found that monetary development has a positive and significant effect on the supply of facilities studied banks. In addition, other variables such as GDP and bank size have positive and significant effect and interest rate have negative and significant negative effects on the supply of facilities to banks.

Chen and Lu (2021) in a recent study examined the factors affecting macroeconomic performance in banks in different cities of China. Using data from commercial banks in 2005-2014 and FDI, they found that there is a positive and strong correlation between GDP per capita and urban growth in this country with the performance of commercial banks.

Golizadeh et al. (2021) conducted a research entitled identifying key factors affecting banking resource equipping and providing an adaptive model. In this study, Iranian banks and Islamic banks were compared between 2012-2019 and 2012-2019 and GMM econometric methods, respectively. The results showed that indicator of legal deposit rate, non-current demand, inflation and exchange rate have negative and significant effects. Stock return and return on capital and asset return, GDP, investment deposit and loan interest deposit have positive and significant effects on equipping of banking resources in Iran and International banks.

Materials and methods

Since in this study, a self-explanation model with non-linear distributed lag (NARDL) is used to investigate the effects of independent variables on credit supply, so in this part, first the pattern of sub-description based on the variables used in this paper, and then the related information collection variables are introduced. To investigate the asymmetric relationships between economic variables in the short-term and long-term from the model of Shin et al. (2014), through the development of the linear auto regressive distribution lag model with its asymmetric mode, i.e. the model with non-linear auto regressive distribution lag (NARDL) is formed, used.

Nonlinear ARDL is an extended form of ARDL model. NARDL is a new approach used to specify the long-run and short-run asymmetrical relationship between the economic variables. The asymmetries form the non-linear relationships. The NARDL model has the ability to dynamically model aggregation and asymmetry compared to other linear and traditional econometric methods (Zhu et al., 2022). Based on the economics literature and the empirical studies, we can propose the following model to investigate the independent variables on credit supply.

$$GF_t = \beta_0 + \beta_1 NCR_t + \beta_2 IR_t + \beta_3 INF_t + \beta_4 GDPG_t + \beta_3 BS_t + u \quad (1)$$

Where; *GF* indicating the supply of facilities and bank credits (dependent variable), *NCR* indicating non-current receivable, *IR* indicating the interest rate of banking facilities of the Agricultural Bank in Iran, INF the inflation rate of the provinces, *GDPG* the growth of Iran's gross domestic product and BS indicating the size of the bank (the ratio of the assets of the Agricultural Bank to the total bank assets in the province).

The asymmetric long-run relationship without a constant term can be represented as:

$$GF_t = B_1^+ NCR_t^+ + B_1^- NCR_t^- + \beta_2^+ IR_t^+ + \beta_2^- IR_t^- + \beta_3^+ INF_t^+ + \beta_3^- INF_t^- + \beta_4^+ GDPG_t^+ + \beta_4^- GDPG_t^- + \beta_5^+ BS_t^+ + \beta_5^- BS_t^- + u_t \quad (2)$$

In the above relationship, positive and negative beta coefficients (β_i^+ and β_i^-) are long-term asymmetric coefficients of independent variables. In equation (2), partial sum of positive and negative changes of variables is shown with positive and negative signs, respectively. For example, the positive and negative changes of the NCR variable are defined as follows:

$$NCR_t^+ = \sum_{i=1}^{t} \Delta NCR_t^+ = \sum_{i=1}^{t} \max\ (\Delta NCR.\ 0)$$

$$NCR_t^- = \sum_{i=1}^{t} \Delta NCR_t^- = \sum_{i=1}^{t} \min\ (\Delta NCR.\ 0) \quad (3)$$

Equation 2 can be rewritten as a NARDL model in the form of error correction (ECM) as follows:

$$\begin{aligned}\Delta GF_t = {} & \alpha + \lambda_1 GF_{t-1} + \lambda_2^+ NCR_{t-1}^+ + \\ & + \lambda_2^- NCR_{t-1}^- + \lambda_3^+ IR_{t-1}^+ + \lambda_3^- IR_{t-1}^- + \\ & + \lambda_4^+ INF_{t-1}^+ + \lambda_4^- INF_{t-1}^- \\ & + \lambda_5^+ GDPG_{t-1}^+ + \lambda_5^- GDPG_{t-1}^- + \\ & + \lambda_6^+ BS_{t-1}^+ + \lambda_6^- BS_{t-1}^- + \\ & + \sum_{j=1}^{k_1} \gamma_{1j} \Delta GF_{t-j} + \sum_{j=0}^{k_2} \gamma_{2j}^+ \Delta NCR_{t-j}^+ + \\ & + \sum_{j=0}^{k_2} \gamma_{2j}^- \Delta NCR_{t-j}^- + \sum_{j=0}^{k_3} \gamma_{3j}^+ \Delta IR_{t-i}^+ + \\ & + \sum_{j=0}^{K_3} \gamma_{3j}^- \Delta IR_{t-i}^- + \\ & + \sum_{j=0}^{K_4} \gamma_{4j}^+ \Delta INF_{t-i}^+ \sum_{j=0}^{K_4} \gamma_{4j}^- \Delta INF_{t-i}^- + \\ & + \sum_{j=0}^{K_5} \gamma_{5j}^+ \Delta GDPG_{t-i}^+ \sum_{j=0}^{K_5} \gamma_{5j}^- \Delta GDPG_{t-i}^- + \\ & + \sum_{j=0}^{K_6} \gamma_{6j}^+ \Delta BS_{t-i}^+ \sum_{j=0}^{K_6} \gamma_{6j}^- \Delta BS_{t-i}^- + \varepsilon_t \end{aligned} \quad (4)$$

In equation (5), the coefficients (λ_1, λ_2^+, λ_2^-, λ_3^+, λ_3^-, λ_4^+, λ_4^-, λ_5^+, λ_5^-, λ_6^+, λ_6^-) represent long-term coefficients, and the coefficients (γ_1, γ_2^+, γ_2^-, γ_3^+, γ_3^-, γ_4^+, γ_4^-, γ_5^+, γ_5^-, γ_6^+, γ_6^-) represent short-term coefficients and ε_t is the error term.

The statistics and information of the variables were collected using the Central Bank's time series database, economic indicators, Iran Statistics Center, and the financial statements and balance sheets of agricultural banks of different provinces for the period 2007 to 2020.

Results and discussion

In the first step, the stationarity test of research variables was taken into consideration. In other words, according to the nature of the time series of the variables and in order to avoid any errors in the way of estimating the patterns, the sum of the variables' dependence should be determined. Therefore, the usual tests of panel data, including Fisher-Dickie-Fuller Generalized (F-ADF), Im-Sons-Shin (IPS) and Levin-Lin-Chu (LLC) were used. But in order to check the presence of non-linear unit root, relevant tests were performed. The results can be seen in Table 1. It is clear that all the variables have a single root and are stationary in the first difference. Therefore, all three tests suggest the sum of degrees of dependence of one or I(1).

Moreover, the presence of nonlinear behaviors in the research data were investigated using Yukar-Ama and Amir Mahmoud Aghlu-Amay test. According to the results of the Table 2, the presence of non-linear root in all variables has been confirmed. Therefore, in modeling the relationships between variables it is necessary to pay attention to this important finding and avoid using linear patterns. Hence, taking into account the non-stationary variables and the non-linear effects on the variables, it is possible to examine the relationships between research variables in the long term.

Following the preliminary investigations, an attempt was made to estimate the self-explaining pattern with extensive non-linear interruptions (NARDL). The results of the estimates are reported in Table 3.

Moreover, the positive momentum coefficient of bank in the long run is the highest among all factors. More accurate expression, one percent increase in positive bank size shock would result in a 32.0 percent increase in Agricultural Bank credit supply. In other words, horizontal development of bank in terms of branches increase and investments in modern banking technologies that are considered as an asset increase was the most important factor in increasing the credit supply in Keshavarzi Bank during the period.

GDP growth is the second most important long-term

Result	F-ADF		IPS		LLC		
	First difference	Level	First difference	Level	First difference	Level	
I(1)	-7.55*	-1.43	-4.40*	-0.23	0.82	0.82	GF
I(1)	-5.67*	-1.63	-3.36*	-0.44	0.62	0.62	NCR
I(1)	-5.32*	-1.97	-5.97*	-0.63	-0.75	-0.75	IR
I(1)	-6.99*	-1.56	-4.63*	-1.29	-1.11	-1.11	INF
I(1)	-5.18*	-2.82	-5.33*	-0.98	-0.91	-0.91	GDPG
I(1)	-6.64*	-0.89	-3.19*	-1.01	-0.65	-0.65	BS

Note: Variables are in natural logarithm. * Significantat 10% level
Source: Authors computation

Table 1: The results of the stationarity test of the variables.

	Non-linear unit root		Symmetric nonlinear unit root
	UO	EO	EO
GF	-1.01**	4.25***	1.01
NCR	-1.52***	5.32***	1.23
IR	-1.34***	4.94***	1.11
INF	-2.12***	5.64***	1.19
GDPG	-1.61***	5.39***	1.21
BS	-1.73***	4.75***	1.53

Note: **and*** are significant at 5 and 1 percent levels, respectively.
Source: Authors computation

Table 2: Nonlinear unit root test results.

coefficient. More precisely, a percentage increase in positive momentum of this variable leads to an increase in credit supply by 0.28% in the long run. The same coefficient for the negative momentum of this variable is estimated to be -0.19. Provincial inflation is identified as the third most influential variable in table (3). Although this association may at first look attractive and considerable, the fact is that the increase in the supply of facilities due to higher inflation does not necessarily mean the growth of the real indicators of the agricultural sector, because as a result of the increase in the general level of prices (which is associated with inflation in different commodity groups based on causal relationships) farmers need more facilities to meet their constant needs and thus the value of the bank's facilities rises without bringing the output boom. Investment in the sector or business development, on the other hand, requires financing more. On the other hand, inflation can result in more pressure on the government to provide subsidized comfort facilities.

According to the results, the bank's non-current receivable can only have a negative impact on the supply of credit. The long-run positive momentum coefficient of this variable is -0.18. In the analysis of this result, it can be said that as the amount of non-current demand of a bank in the previous period increases, it will create a lot of difficulties for banks. One of the main problems and obstacles that will create for banks is that it will reduce the power of bank facilities to be paid by banks and financial institutions in the coming period.

Moreover, the positive momentum coefficient of interest (IR) is estimated to be 0.04 in the long run. Although the increase in facility productivity is the basis of more propensity and desire by KESB to offer facilities, it should be mentioned in full coordination with the national interest rate and inflation, and the Agricultural Bank should seek to reduce margin of profit by improving productivity (difference between the facility interest rate and the deposit profit rate). Moreover, a significant portion of the Bank's facilities are allocated in the form of Comment (subsidized) facilities to strengthen the infrastructure of the agricultural sector; an increase in the rate of such facilities will actually mean an increase in the government's burden of spending. Therefore, proposal increase of utility rates as a factor for extending the supply of facilities to be considered.

Wald's test is used as an estimate to investigation the symmetry or asymmetry of positive and negative shocks of the variables. The results of this test are shown in table 4. The null hypothesis in Wald's test is based on the symmetrical effect of positive and negative shocks. According to the obtained results, the null hypothesis of this test is rejected for all variables at the 5% error level. hence, indicates that the positive and negative shocks of the variables have asymmetric effects on GF of the Bank of Agriculture in Iran.

Variable	Long-term		Short-term	
	Coefficient	Probability	Coefficient	Probability
NCR^+	-0.18	0.03	-0.07	0.04
NCR^-	0.05	0.11	0.08	0.07
IR^+	0.04	0.14	0.02	0.09
IR^-	-0.08	0.12	-0.01	0.12
INF^+	0.23	0.03	0.03	0.05
INF^-	-0.15	0.06	-0.04	0.05
$GDPG^+$	0.28	0.01	0.08	0.03
$GDPG^-$	-0.19	0.02	-0.11	0.02
BS^+	0.32	0.07	0.09	0.08
BS^-	0.06	0.09	0.07	0.11
ECT(-1)	-	-	-0.54	0.03

Source: Authors computation

Table 3: Long-term and short-term coefficients in estimated NARDL model.

Variable	Long-term	Short-term
	Chi-square statistic (probability)	Chi-square statistic (probability)
NCR	9.56 (0.02)	8.23 (0.04)
IR	1.25 (0.03)	1.42 (0.04)
INF	8.62 (0.02)	1.36 (0.02)
GDPG	7.91 (0.04)	6.28 (0.04)
BS	7.43 (0.04)	1.97 (0.01)

Source: Authors computation

Table 4: The results of the test of asymmetry in the effects of variables.

Conclusion

As one of the specialized banks active in Iran's economy, Agricultural Bank plays an undeniable role in financing agricultural activities on the one hand and implementing government support policies (such as guaranteed purchase and agricultural insurance) on the other hand. Due to the expansion of agricultural activities throughout the country and the development of related industries in recent decades, the demand for loans granted by the said bank has increased.

So that during the studied period in the agricultural sector, the Bank of Agriculture has paid loans in the amount of 22 thousand trillion Rials.

Considering the different needs of different provinces for bank loans, due to the difference in the volume, composition and type of agricultural activities, the identification and analysis of factors affecting the supply of facilities based on provincial panel data was considered in this study. In this regard, the data of the period 2007 to 2020 and the self-explanatory model with a wide non-linear interval based on panel data have been used. Based on the investigations and tests, the existence of a non-linear relationship between the independent variables and the dependent variable (credit supply) was confirmed. In other words, positive and negative impulses have different effects on credit supply and it is necessary to estimate these two effects separately.

The results of the estimation model showed that the bank size variable (the ratio of agricultural bank assets to total bank assets at provincial levels) was the most important driver of credit supply in the period under review. Based on this, the bank's policy of expanding horizontally and increasing the number of branches in cities and rural areas (which is an example of increasing assets) along with the slogan "Agricultural Bank, the Bank of All People of Iran" which has been an important factor in attracting capital and equipping the bank's resources (and naturally has improved the capacity to supply facilities), has been able to have a positive and significant effect on the injected credits to the agricultural sector. Of course, it should be noted that the estimated long-term and short-term positive momentum coefficients (0.32 and 0.09) were actually the average effect for all provinces in the study period. Based on this, it is recommended to increase investment in the field of new banking technologies and try to create transformation in sync with the developments of the international banking system (which is a kind of asset increase and also helps to improve productivity).

GDP growth was identified as the second variable in terms of intensity of impact. Naturally, the real growth of the economy is a factor for the improvement of banking performance indicators and therefore it is expected to have a positive effect on the injection of more credits. The provincial inflation rate has also had a positive and significant effect. The increase in the general level of prices has actually led to an increase in the cost of production, and therefore, in order to meet the demand for credits, the volume of granted facilities has also increased. As mentioned, this effect, contrary to what may appear on the surface, does not necessarily mean a positive effect on the actual production of the agricultural sector, and perhaps the volume of facilities has increased to maintain the previous level of production.

The interest rate of the facility has also shown a direct and significant effect on the supply of credits (long-term and short-term). Considering the important role of the Agricultural Bank in providing low-cost facilities for agricultural activities, the proposal to increase the interest rate of the facility as a factor for increasing the supply of credits should be raised with caution, because it will actually mean an increase in the financial burden of the government (in case of no change in the interest rate of the facility) or an increase in the cost of production, or both.

Based on the obtained results, non-current receivable is the only variable with an inverse (indirect) effect. Available statistics and information show that the volume of doubtful and overdue claims in the Bank of Agriculture is at a high level. It is obvious that non-repayment of granted facilities practically limits the capacity of injecting resources and responding to credit demand. Therefore, it is recommended that the Agricultural Bank in Iran, put the control of non-current receivable in a more effective way (especially through the detailed examination of the neediest borrowers and desirable characteristics of the recipients of the facilities, including their qualifications.) in its policy priorities and in this way, reducing the credit risk, and provide more effective services in the financing of the agricultural sector.

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Volume XVII Number 1, 2025

Incorporating Systems Engineering into Project Management Enhances Operational Efficiency

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Abstract

Project management (PM) orchestrates multiple processes and resources while ensuring compliance with quality standards. But as projects become increasingly complex, lifecycle PM struggles to optimize risk mitigation strategies. Nevertheless, Systems Engineering (SE) may complement PM in managing complex projects and mitigating associated risks. Testing this hypothesis, this study assesses whether integrating SE into PM improves project execution. Our qualitative research and data analysis highlight the adaptability of SE in addressing intricate issues. Moreover, our findings demonstrate that incorporating SE into PM methodologies substantially improves the execution of complex projects.

Keywords

Collaboration, project, project management, project manager, systems engineer.

Huguet, S., Bláhová, P., Procházková, R., Saro, J. and Brožová, H. (2025) "Incorporating Systems Engineering into Project Management Enhances Operational Efficiency", *AGRIS on-line Papers in Economics and Informatics*, Vol. 17, No. 1, pp. 31-40. ISSN 1804-1930. DOI 10.7160/aol.2025.170103.

Introduction

Three key factors, namely time, cost, and quality, determine the outcome of a project. In project management (PM), these three boundaries form an equilateral triangle, setting the limits of the project and collectively defining its scope based on the best ratio of these elements (Radujković and Sjekavica, 2017). Any deviation from this equilateral triangle entails a deviation from optimal PM and jeopardizes the success of a project.

A project is an activity with a defined beginning and end, so it does not repeat. By contrast, processes within a project can be repeated and remain consistent (Leong et al., 2014).

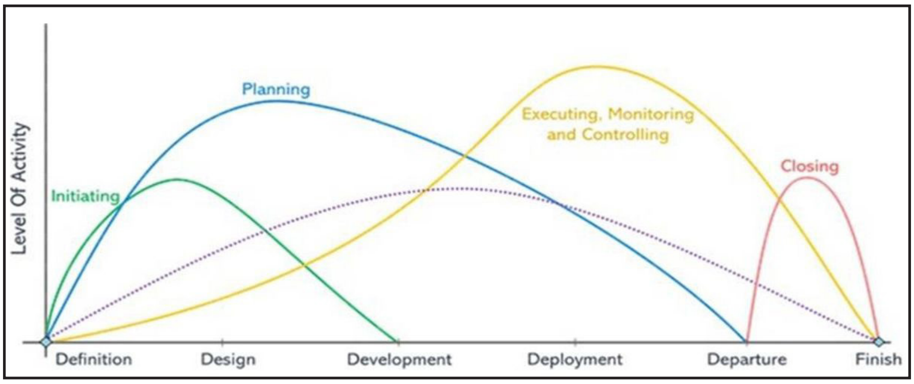
Accordingly, PM adds value to an organization, proving essential to the growth and development of modern industry (Galli, 2020b).

PM success has long been studied in both scientific and practitioner literature (Varajão et al., 2022). The better PM processes are, the most likely a project will be completed with high quality (Schoper et al., 2017). But improving PM requires reacting to every opportunity and overcoming challenges. Unlike processes and operations, projects are unique and must be addressed individually (Learning, Kerzner and Belack, 2010), considering both shared and specific characteristics of human, material, and mixed resources in leading a project (Wagner, 2019). As a time-bound and comprehensive set of activities and processes aimed at introducing, creating, or changing something specific, a project must be managed differentiating individual tasks from major activities encompassing many processes (Project Management Institute, 2008).

As projects become increasingly complex (Müller and Turner, 2007), lifecycle-focused PM struggles to manage associated risks (Mabelo and Sunjka, 2017). Nevertheless, applying systems engineering (SE) concepts can improve the management of complex projects and risk mitigation (Iriarte and Bayona, 2021). Because SE processes are adaptable, they are suitable for managing complex problems (Galli, 2020a).

Project lifecycle

Completing a project requires appropriate PM, which can also help to reduce risks in project processes. Increasing control over processes increases the probability that a project will be completed on time (Alzoubi, 2022). The full life cycle of a project is described in Figure 1. All



Source: Chand (2024)

Figure 1: Project management life cycle.

stages (Initiating, Planning, Executing, Monitoring and Controlling, and Closing) can be streamlined by improving PM skills and competitions (Level of Activity).

Figure 1 illustrates the role of project managers across various project phases. Initially, project managers define the project and set objectives. Planning involves a detailed scope, schedule, and resource management. During execution, they implement the plan, monitor performance, and manage changes (Sima, 2022). In closing, they ensure deliverable acceptance and complete documentation. Key skills include leadership, communication, and adaptability (Halushka, 2021).

As outlined in Table 1, increased rates of project failure commonly derive from cost and time overruns (Bilir and Yafez, 2022) and from the lack of consistency between tasks and/or the whole project because current PM practices increasingly fail to manage risks (Hilson, 2014). At the core of these notable deficiencies lies the inability to manage increased complexity.

Effectively mitigating risks associated with increasingly larger and more complex projects requires a new approach to PM (Cristóbal et al., 2018). The systems approach has the potential to improve PM and its practices (Galli, 2020a).

Sector	No. of projects	Cost Overrun (%)	Time Overrun (%)
Atomic energy	12	25	91.67
Civil aviation	47	42.52	91.49
Coal	95	22.11	61.05
Fertilizers	16	25	62.5
Finance	1	100	100
Health and family welfare	2	100	100
I&B	7	42.86	100
Mines	5	0	80
Petrochemicals	3	33.33	100
Petroleum	123	20.33	79.67
Power	107	46.73	60.75
Railways	122	82.79	98.36
Road transport and highways	157	54.14	85.35
Shipping and ports	61	31.15	95.08
Steel	43	18.6	81.4
Telecommunication	69	15.94	91.3
Urban development	24	41.67	100

Source: Singh (2009)

Table 1: Cost and time overruns in infrastructure projects by sector - An enquiry into extents. Causes and Remedies.

The integral role of the systems engineer across the project life cycle

The ('Systems Engineering Guidebook', 2022) defines a system engineer as a professional who applies a systematic, interdisciplinary approach to "designing, integrating, and managing complex systems over their life cycles". This role involves coordinating various engineering teams, ensuring that all system components work harmoniously, and meeting requirements and performance standards. The system engineer focuses on the holistic functionality of a system, encompassing its development, operation, maintenance, and eventual decommissioning (Oehmen et al., 2012), while addressing both technical and managerial aspects.

Several studies have already addressed the relationship between the systems engineer and the project manager towards improving processes and, thus, successfully completing the whole project (see Table 2). These studies have delved into inherent risks, risk mitigation strategies, and the scale of various projects. Yet, despite their extensive analysis, no study has comprehensively examined the role of the systems engineer throughout the project life cycle and its distinct phases.

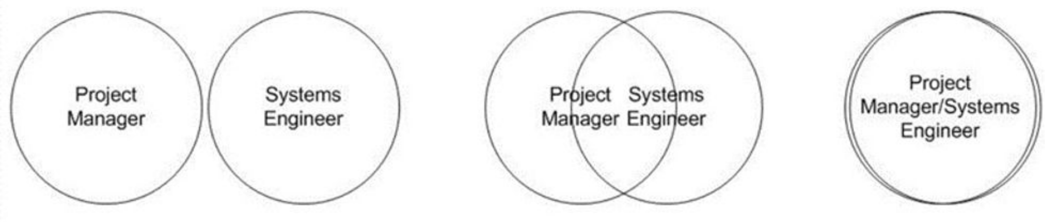
R. Turner, A. Squires	Relationships between Systems Engineering and Project Management	2024
Brian J. Galli	The Application of Systems Engineering to Project Management A Review of Their Relationship	2020
João Varajão, António Trigo, José Luís Pereira, Isabel Moura	Information systems project management success	2021
	Guide tom the Systems Engineering Body of Knowledge v2.10.	2018
João Varajão	The many facets of information systems (+projects) success	2018

Source: Authors

Table 2: Technical articles and other publications focusing on project improvement through a systems engineer (2024).

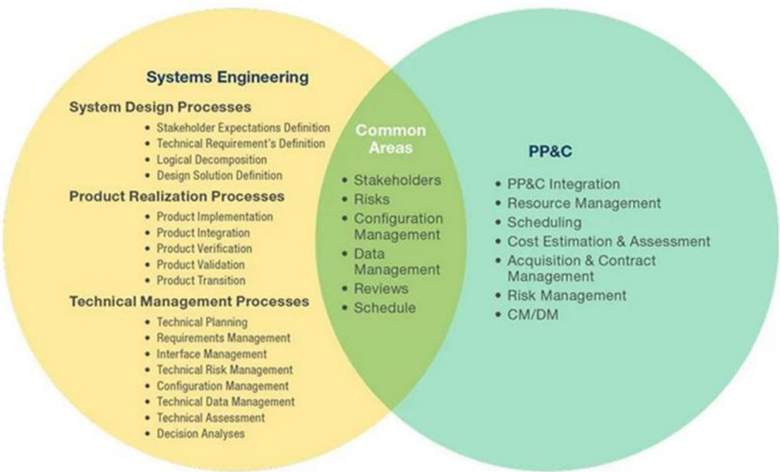
Systems engineers can help to ease the workload of project managers, enabling them to focus on more sophisticated tasks, such are setting project targets (Munns and Bjeirmi, 1996), managing resources and budgets, and communicating with sponsors and stakeholders ('NASA Systems Engineering Handbook', 2007). Systems engineers can also tackle more technical aspects of the project, including system design, development, and maintenance, project planning and monitoring, and risk confrontation (Turner and Squires, 2024). Thanks to this technical support, project managers have more time to focus on activities of the overall project and on project sponsors (Kordova, Katz and Frank, 2018). As shown in Figure 2, these functions are interrelated, overlapping to some extent.

SE is essential in project organization, particularly in three main tasks: managing technical aspects, overseeing the project team, and controlling costs and schedules. SE makes technical, cost, and schedule decisions, providing this information to PM. In turn, Project Planning and Control (PP&C) manages project costs and schedules (*SEH 2.0 Fundamentals of Systems Engineering - NASA*, no date), ensuring that the project delivers a technically sound system within budgetary and time constraints. SE and PP&C partly overlap, but SE provides technical inputs, while PP&C offers programmatic, cost, and schedule inputs (Figure 3)..



Source: Turner and Squires (2024)

Figure 2: Overlap between project roles.



Source: SEH 2.0 Fundamentals of Systems Engineering - NASA (2019)

Figure 3: Systems Engineering in Context of Overall Project Management.

Materials and methods

Collaboration between systems engineers and project managers

The present study employed a qualitative research design aimed at achieving analytical rather than statistical generalization typical of quantitative research. While statistical generalization seeks to draw inferences about a population based on empirical data from a sample, analytical generalization requires comparing empirical case study results with pre-existing theoretical frameworks. This study predominantly relied on semi-structured interviews with project managers.

The interviewees were project managers, each of whom leading teams of 10-15 members. These managers were employed by corporations in the Czech Republic, each of which with a workforce exceeding 250 employees. The sample comprised 10 seasoned project managers recognized as subject matter experts in their respective domains. These individuals were selected based on their professional standing, educational background, and extensive experience, which collectively underscored their expertise in the field (Figure 4).

The following measures were implemented to ensure the trustworthiness (internal validity) of the qualitative findings:

Triangulation: A finding was deemed trustworthy and valid if mentioned in at least three interviews. This qualitative study based on semi-structured interviews precluded statistical analysis, typical of quantitative studies. The convergence of similar topics across three different interviewees served as a triangulation procedure to enhance the internal validity of the study.

Cross-validation: Throughout the interview process, cross-validation was performed to assess the consistency of respondents' agreement with the provided definitions (respondent validation).

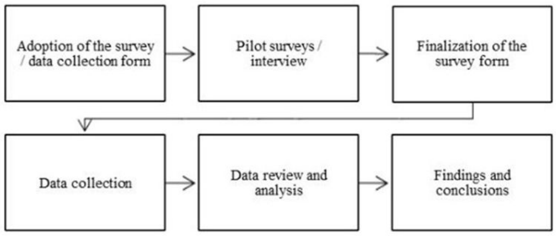
To ensure confirmability, the extent of objectivity was consistently examined throughout the research process using the following techniques:

Unbiased Questioning: The interview questions were carefully crafted to ensure that they were clear and unbiased, so that the responses were not influenced by the wording.

Error minimization: Measures were implemented to minimize errors stemming from initial impressions and early assumptions, thereby enhancing the generalizability of the research findings to the broader population (external validity—fittingness).

The research sampling procedure was also carefully designed to avoid bias towards either PM or SE. An equal number of participants from both domains were interviewed to ensure balanced representation.

Highly regarded experts from the PM community were selected based on their recognized expertise and contributions to the field.

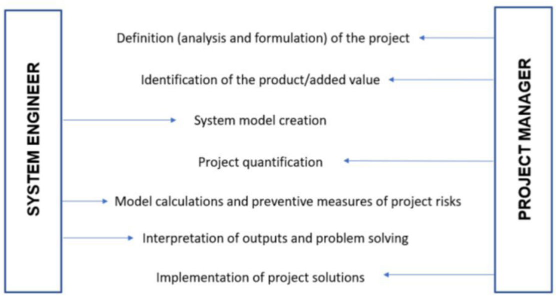


Source: Authors

Figure 4: Study methodology.

Results and discussion

SE combines elements from many areas: operations research, systems modelling, specification writing, risk management, requirements development and PM. PM is all about achieving practical results, completing tasks and repairing things. When working on a large and complex project or on a project requiring a deep technical background, collaborating with a system engineer may prove particularly helpful, even more so if the project manager lacks technical skills. Project managers and system engineers can bridge gaps on the life cycle of a project and work together harmoniously until its completion. To this end, both of them must feel that they are equal partners, collaborating to meet all stakeholders' expectations (Figure 5).



Source: Authors

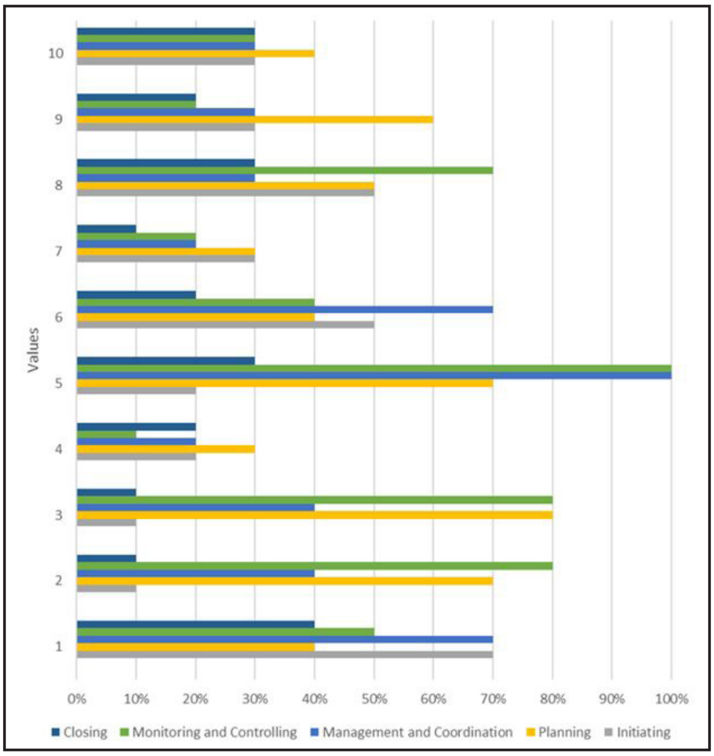
Figure 5: Collaboration between systems engineer and project manager.

Nearly 90% respondents stated that they already leveraged the expertise of systems engineers during the implementation or coordination phases of projects, with unanimous agreement on their efficacy and contribution to successful project completion. Depending on the project life cycle, which is divided into distinct phases, 45% project managers agreed with the assertion that a systems engineer should be included in the team from inception to conclusion. Additionally, 90% respondents believe that the systems engineer should be primarily involved in the project during the Management and Coordination, and Monitoring and Controlling phases. A slightly lower percentage (78%) highlighted the importance of the systems engineer's engagement across all phases — Initiating, Planning, Management and Coordination, Monitoring and Controlling — excluding only the Closing phase. Figure 6 shows the percentage of weights assigned to each phase of the project cycle, indicating the level of involvement required from the system engineer in each specific phase.

The role and significance of a systems engineer in project development greatly depends on the size and type of project. In smaller projects, project managers and senior technical staff often take on the responsibilities of a systems engineer, rendering the role less critical. However, in larger projects, the role of a systems engineer becomes indispensable, sometimes requiring an entire department. The need for systems engineers also varies with the type of project — technical projects, such as manufacturing, heavily rely on systems engineers, while their involvement in case studies or purely financial projects may be minimal. Overall, systems engineers are crucial for minimizing errors, providing clear structure, and enhancing project efficiency, tailoring their involvement to the specific requirements of each project.

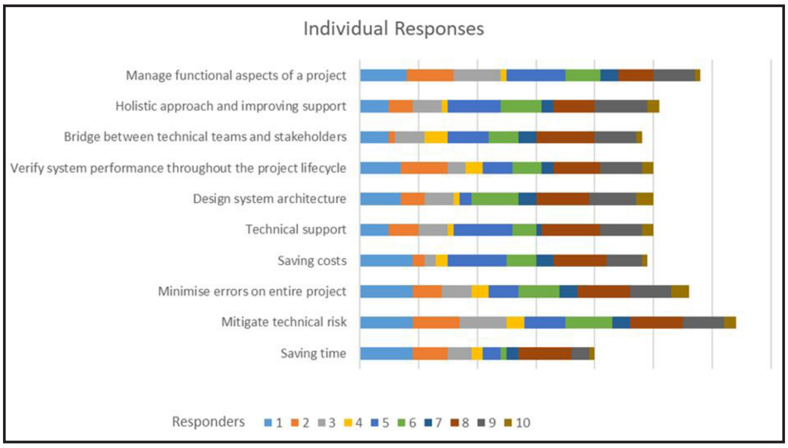
Considering the above, the respondents had the opportunity to express their judgment in text. Respondents assigned weights ranging from 1 to 10 to each task activity (Figure 7), reflecting the perceived importance of the systems engineer's role within a project. These weights serve as indicators of the significance attributed to each task, demonstrating the critical influence of SE on the overall success of a project.

Through close collaboration between project managers and systems engineers, organizations can effectively manage project risks and identify potential roadblocks before they impact the project. An integrated approach to PM requires organizations to clearly understand the project scope, objectives, and stakeholders. This understanding should be



Source: Authors

Figure 6: Respondents' answers by phase of the life cycle of a project.



Source: Authors

Figure 7: Individual responses.

communicated to all stakeholders and recorded in project documentation. An integrated approach to PM, especially in managing stakeholders' demands, yields successful risk mitigation and project coordination. The results below synthesize responses of the experienced project managers.

The main collaboration steps are:

1. Definition (analysis and formulation) of the project
2. Identification of the product/added value
3. System model creation
4. Project quantification
5. Project review
6. Interpretation of outputs and problem solving
7. Project completion

1. Definition (analysis and formulation) of a project

For successful PM, the new product of a project must be clearly defined, providing a clear focus for the entire process. This initial definition should guide PM efforts, keeping the project aligned with its objectives and on track. Therefore, the first step of the PM process is to clearly and concisely define the new product, including its goals, objectives, and scope upon consensus among all stakeholders for a common understanding of the purpose of the project.

A significant challenge arises when a project manager is unable to accurately define the individual steps of a complex project, particularly in an unfamiliar domain. Mitigating this risk requires involving a systems engineer from the inception of the project. This collaboration ensures that no essential questions are overlooked and that all queries are addressed precisely, correctly, and promptly. The systems engineer's involvement also reduces human error during project implementation by providing clear, detailed information to each team member about their specific tasks and priorities.

Engaging a systems engineer facilitates productive discussions with the project sponsor, allowing professional inquiries about systems aspects of the project, the proposed product and its requirements and expectations. This approach not only strengthens product specifications but also saves time and reduces overall project costs. Prolonged projects tend to be more expensive and erode client confidence in the project manager's capabilities. Therefore, early and continued collaboration between the project manager and the systems engineer promotes sustained project efficiency, cost-effectiveness, and stakeholder trust.

2. Identification of the product/ added value

In the subsequent step, a comprehensive and detailed project plan is tailored to the specific project. This plan should encompass the timeline, tasks, resources, and budget necessary for project completion. With input from the systems engineer, the project manager addresses areas requiring additional expertise or guidance. Tasked with articulating expectations and providing a detailed description of the new product or service, the project manager assumes a greater responsibility than the systems engineer during this step. The systems engineer's role consists of providing professional insights and sharing comments to support the project manager's decisions and to ensure technical accuracy.

3. System model creation

In the third step, the project plan is executed, which involves task assignment, resource management, and progress monitoring. The project manager is responsible for ensuring that all tasks are completed on time and within the allocated budget. Recent advances in AI tools and supports offers opportunities to accelerate processes, to simplify tasks, and to reduce human errors. However, given the breadth of these advancements, a project manager cannot comprehensively master all new programs and tools essential for informed decision-making. Consequently, project managers often rely on their existing practical experience, which is insufficient on its own, so an organized framework must be established to integrate these new tools and methodologies systematically.

4. Project quantification

Properly planning the budget is essential to meet project timelines, to control costs and to achieve the expected results. Key questions every project sponsor wants answered include: How long will it take to prepare and complete the project? What is the total cost, and does it fit within the set budget? How will the financial aspects of pilot implementation or gradual sector development within the company's existing system differ? Will the budget or implementation time be exceeded?

Addressing these questions, the project manager initiates the planning process, leveraging their skills in team leadership, motivation, and task estimation based on past projects.

However, there is a significant risk of deviation in judgment without comprehensive analysis and support. A systems engineer can provide professional advice, offering different perspectives when necessary. This collaborative approach fosters more precise calculations and helps mitigate the risks of delays and unforeseen costs. The systems engineer's input ensures a detailed evaluation of technical requirements and potential issues, enhancing the accuracy of budget and timeline estimations, thus ensuring the project's success.

5. Project review

The fifth step is to review the project, a critical phase in the PM process that allows the project manager to assess progress, identify issues, and make necessary adjustments.

Leveraging the systematic perspective of a systems engineer highly skilled in IT systems can be particularly beneficial at this stage. The systems engineer's education and experience enable the project manager to identify and mitigate risks effectively. Additionally, the systems engineer can introduce preventive measures and other relevant solutions, further enhancing the project's success and stability. This collaborative review ensures that all aspects of the project are thoroughly evaluated, leading to informed decisions and continuous improvement.

6. Interpretation of outputs and problem solving

Each project is unique, and while a project manager can prepare for anticipated problems, unexpected issues may cause additional costs and delays. A systems engineer must be engaged in the project from its inception to address unforeseen challenges proactively. The systems engineer's expertise can help to identify potential risks and implement preventive measures early on, thereby facilitating progress in subsequent phases of the project. This collaborative approach enhances the project manager's ability to interpret outputs accurately and to resolve issues efficiently. As a result, the project stays on track and within budget.

7. Project completion

The final stage of the project involves introducing solutions, relying on the collaboration between the project manager and the systems engineer. Based on high-quality skills and mutual trust, this partnership ensures adherence to timelines and budgets while maximizing client satisfaction. The project manager leads the effort, supported by the systems engineer's professional advice in addressing technical challenges. Investing in a systems engineer from the beginning and throughout the project helps to pre-empt issues, ensuring smooth progress.

In this stage, the focus is on confirming that all deliverables meet quality standards and client expectations. With the systems engineer's support, the project manager conducts the final testing, user training, and formal handover of deliverables. Ensuring a seamless transition and providing the necessary post-implementation support sets the project on a path towards success and fosters client trust.

Conclusion

The integration of Systems Engineering (SE) into Project Management (PM) practices has demonstrated considerable potential in enhancing operational efficiency, improving project outcomes, and mitigating risks, particularly in complex project environments. This study has explored the complementary roles of project managers and systems engineers, highlighting the critical intersections where collaboration between these professionals' results in greater project success.

By adopting a systems approach, project managers are better equipped to handle the growing complexity and scope of modern projects. Systems engineers contribute significantly to technical decision-making, risk assessment, and problem-solving, while project managers focus on achieving strategic objectives, stakeholder communication, and overall project coordination. This partnership allows for a more balanced distribution of responsibilities, ensuring that technical and managerial aspects are equally addressed throughout the project lifecycle.

The empirical findings from this study confirm that the active involvement of systems engineers —particularly in the initiation, planning, and monitoring phases—has a direct and positive impact on project efficiency, cost control, and timely delivery. The ability of SE to provide systematic analysis, anticipate potential risks, and implement structured processes has proven invaluable in supporting project managers and fostering a collaborative environment focused on project success.

Moreover, the study underscores the importance of early and continuous integration of SE into PM practices. Early engagement of systems engineers helps to clarify project objectives, refine system requirements, and establish realistic budgets and schedules. Continuous collaboration throughout the project lifecycle further ensures adaptability and responsiveness to emerging challenges, reducing the likelihood of costly delays or quality compromises.

Despite these positive outcomes, the research also acknowledges the need for more standardized frameworks and methodologies that facilitate effective collaboration between project managers and systems engineers. Future research should focus on developing integrated models that clearly delineate roles, responsibilities, and decision-making processes. Additionally, further studies could explore the impact of SE integration in different industry sectors and project types, including those less reliant on technical systems, to assess the universality and scalability of the approach.

In conclusion, this study highlights the significant value of incorporating Systems Engineering into Project Management. As projects continue to increase in complexity and stakeholder expectations grow, fostering interdisciplinary collaboration will be essential for achieving sustainable project success. Organizations that recognize and support this integrated approach are more likely to deliver high-quality, timely, and cost-effective outcomes that meet or exceed stakeholder expectations.

SE should be incorporated into projects to enhance operational efficiency and support PM. These findings open up opportunities for further research, highlighting the integral role of SE in successful project execution.

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Major Crops Water Requirements and Automated Irrigation Scheduling System

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Abstract

Agriculture is a critical factor that impacts a country's economy. The agriculture sector uses 70% of the available fresh water. There are challenges in water management and irrigation scheduling that require resolution. Farmers are using traditional irrigation methods that use a lot of water with low water efficiency. Smart irrigation and farm management technology is crucial to sustainable agriculture, as it saves water and provides farmers with more information about crop water requirements. However, managing irrigation water is a complex task that depends on factors such as soil, weather, and environment. Robust modeling is necessary to accurately estimate the water requirements of a crop. In this we developed a smart irrigation model to automate the irrigation system according to water requirements of crops. To estimate the water requirements of crops a review was done on different crop water requirements and crops features. To develop the automated irrigation system an analysis is done on different irrigation methods, irrigation scheduling and requirements of irrigation scheduling. The proposed system is used to automated irrigation system and real time data is sent to think speak server for regular monitoring. The developed automated irrigation system is working up to expectations and help farmers to control the irrigation and conserve water by avoiding over irrigation.

Keywords

Internet of Things, water management, IoT, sensors, smart griculture, Irrigation Efficiency.

Kaur, A., Bhatt, D. P. and Raja, L. (2025) "Amajor Crops Water Requirements and Automated Irrigation Scheduling System", *AGRIS on-line Papers in Economics and Informatics*, Vol. 17, No. 1, pp. 41-50. ISSN 1804-1930. DOI 10.7160/aol.2025.170104.

Introduction

Agriculture uses up to 70% of the world's water resources, making efficient water use crucial for preserving water resources for the future. The traditional irrigation system is widely used by farmers. Surface irrigation, which uses gravity to deliver water to crops, is classified into three main types: border, basin, and furrow systems. The basin system has level, diked areas, while the border system has rectangular, sloping borders. Furrows control flow and prevent flooding by creating channels with water leaking through the walls and bottom of furrows (Saggi and Jain, 2022). Sprinkler irrigation is another method for controlled water distribution, such as rainfall, which can be used for various applications, including industrial, residential, and agricultural. Irrigation sprinklers can be used for various applications, including industrial, residential, and agricultural (Abo-Zahhad, 2023). Drip irrigation is the preferred option, as it is the most effective means of supplying water and nutrients to crops. The system ensures that every plant receives the necessary nutrients and water precisely and timely to its root zone. This technique can save energy, water, and fertilizer while increasing production. Development of agriculture depends on water, particularly in dry and semi-arid regions. By using information and communication technologies (ICTs) to replace outdated methods with more advanced ones, the Indian economy has undergone a substantial transformation (Kondaveti et al., 2019). Services such as crop management, plant disease prevention, smart water management, IoT agriculture, crop management, crop tracking, and geospatial imagery have been made possible. India is one of the countries with the highest consumption of water for irrigation. Understanding the diverse, complex, and unpredictable agricultural ecosystems through ongoing analysis, measurement, and observation of physical elements and occurrences is crucial to overcoming these challenges. DSS (decision support system) should be used as a tool for farm management, assisting farmers in selecting which areas require irrigation and how much water is required. To achieve efficient and efficient water usage, agricultural irrigation scheduling is an essential task. Applying the proper amount of water at the correct time is a key component of good irrigation scheduling (Tace et al., 2022). To understand the geographical variations in ET (evapotranspiration), irrigation scheduling improves water use efficiency and concentrates on evapotranspiration estimate techniques. Select irrigation applications, incorporate water quality limitations into scheduling and control models, and combine many sensor technologies (Dari et al., 2022). Because irrigation timing is dependent on several variables, including the environment, crop type, subsurface geo-hydrological state, and development stage, it is crucial for increasing agricultural productivity. The current mechanisms for determining irrigation decisions are enforced for certain crops in a particular location, but they might be difficult to apply to other crops and regions. Crop productivity and quality are greatly influenced by the timing and quantity of water applied. For irrigation scheduling, several techniques are used, such as growth phases, leaf water potential, soil moisture base, and pan evaporation (Abioye et al., 2022). The two soil moisture parameters, soil moisture threshold and soil moisture target, at which irrigation automatically starts and stops, are typically the basis for irrigation modeling in land surface models. The parameters are typically adjusted to their optimal values, ensuring that the soil water reservoir is filled precisely and preventing crop water overflow. The main idea is that many variables affect agricultural operations, including climatic, crop, soil, technological, and human aspects. To close this gap, this article provides a novel way to calibrate soil moisture threshold and soil moisture target to reflect the amount of water used for irrigation in every situation: optimal, deficient, or even excessive (Olivera-Guerra et al., 2023).

Irrigation scheduling

In 1996, Howell conducted a study to examine the effects of irrigation scheduling on water use. This is an application approach that can lead to efficient and effective use of water. Modern irrigation techniques can increase this efficiency. However, even with advanced irrigation technology, it is still important to implement irrigation scheduling at the farm level (Ferreira and da Cunha, 2020). When there is insufficient rainfall, evapotranspiration must compensate for the water lost. Effective irrigation scheduling aims to provide the crop with the right amount of water at the right time by calculating crop water requirements, which are then subtracted from the amount of rainfall that falls. This can be expressed as millimeters per day or millimeters per month (Phocaides, 2007). The following parameters are monitored to supply irrigation to crops.

- Oil Moisture Status
- The Water Requirement of Crops

Understanding water quality, soil, weather, crop, and drainage conditions is necessary for agricultural production. Reviewing pumping systems' efficiency is necessary. Climate and soil types have a great influence on irrigation, including when and how much water is required. Although estimating irrigation schedules is a complicated procedure, modern technology makes it easier (Ren et al., 2011). The timing of water delivery may be set with fixed or adjustable periods to accommodate the needs of agriculture. To ensure efficiency and proper crop growth, the amount should not be greater than what is required for the crop per application, including salt leaching. Crop yields and net benefits per unit area are examples of standard performance measures (Friedman et al., 2016). The best irrigation schedule satisfies the specified limitations and maximizes the measurement of the output.

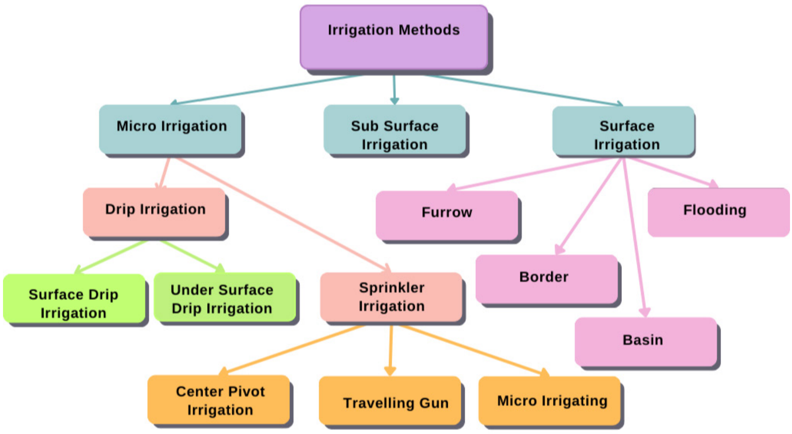
Irrigation scheduling methods

Different irrigation techniques are available for field irrigation, each with its own benefits and limitations. The best approach should be tailored to local conditions (Jackson et al., 2011) Primary irrigation methods, such as bucket watering or wells, are time consuming and require a source of supply. Advanced methods such as sprinkler, surface, or drip irrigation are used in larger areas. The applicability of these is contingent on several aspects, including crop type, technology, previous experience, labor expenses, and benefits (García-Vila and Fereres, 2012; Dwijendra et al., 2022). The application efficiency of various irrigation techniques is shown in Table 1 anb the various irrigation techniques are shown in Figure 1.

Irrigation Methods	Application Efficiency Range %
Surface Irrigation	60-70%
Sprinkler Irrigation	70-95%
Micro Irrigation.	85-95%

Source: Own calculations based on food and agriculture organization data

Table 1: Application efficiency for different irrigation systems.



Source: Own calculations based on food and agriculture organization data

Figure 1: Different irrigation methods.

Border irrigation

Applying water to a field's surface via gravity flow can be done in two ways: either through tiny channels called furrows or by full surface flooding known as basin irrigation (Morris et al., 2015). A contemporary technique, border irrigation uses evenly graded strips of land divided by soil bunds. This method can be fed through small gates, channel banks, spiles, or siphons. With the help of soil bunds, the water slides down the border's slope. Although borders can be up to 800 meters long and 3 to 30 meters wide, they are less appropriate for small-scale farms that rely on manual labor or animal-powered farming methods (Burguete et al., 2014).

Sprinkler irrigation

Using rotating sprinkler heads, water is pumped through a network of pipes and sprayed over crops in a manner like that of natural rainfall. Moreover, sprinklers are used to apply the spray into the air, breaking it up into tiny water droplets that land on the ground. To apply the water evenly, the operational circumstances, pump supply system, and sprinklers must be designed (Cetin and Bilgel, 2002). For most fields, row, and tree crops, it works well. The crop canopy can be sprayed from above or below. However, larger sprinklers are not recommended for delicate crops such as lettuce since the massive water droplets they create could harm plants (Seyedzadeh et al., 2022).

Drip irrigation

It includes the application of water to the soil at extremely low rates (2–20 l/h) by dripping it from small diameter plastic pipe systems connected to emitters or drippers. Another name for it is trickling irrigation. Unlike surface irrigation and sprinkler irrigation, which typically irrigate the entire agricultural area, water is administered very close to plants, wetting only the soil where the roots grow. It works best when there are one or more devices connected to every plant, such as in the case of vine crops, trees, and row crops (vegetables, fruit). Because building a drip system costs a lot of money, it is only considered a viable solution for high-value crops (Pereira et al., 2007; Torres-Sanchez et al., 2020).

Selecting an irrigation method

Selecting an irrigation system is a challenging process. Numerous factors, including crop types, soil, water, and climatic conditions, user knowledge and preferences, capital and operational expenses, and infrastructure accessibility, determine the best option for a user (Jemal and Berhanu, 2020; Zhang et al., 2021)There is no best practice for every circumstance. The following is a summary of the benefits and drawbacks of typical irrigation methods in Table 2. For sandy soils, where excessive percolation is an issue, spray or micro-watering are frequently preferable options than surface irrigation. In dry, windy regions where wind and evaporation losses might be substantial, surface irrigation may be preferable. Water-sensitive crops are better suited for micro irrigation, solid-set, or center-pivot systems as surface irrigation allows less control over application depth. Therefore, small, and frequent irrigations are impractical for these types of crops (Bakhshoodeh et al., 2022; Boutsioukis and Arias-Moliz, 2022)

System Type	Advantages	Disadvantages
Furrow	Water flows in narrow channels and has cheap capital and maintenance expenditures.	High labor costs, poor water management, potential for soil erosion
Level basin	Efficient when designed well; requires less work than a furrow.	Losses from runoff and percolation ponded water and the need to level sloping areas
Border	The drain requires more work and produces more runoff; managing the depth of the infiltration is simpler.	Water flows over the entire surface of the soil.
Solid set	Good water control: Regular irrigation that can be automated; suits odd-shaped fields.	High initial investment: system may obstruct field operations
Set move	Less upfront costs compared to comparable sprinkler systems	Greater application depth, more labor than with traditional sprinkler systems, and inconsistent performance in windy conditions
Center pivot and linear move	High uniformity; Low labor	High initial and ongoing expenditures; Unsuitable for irregularly shaped fields; probable losses due to wind and evaporation
Traveling gun	less expensive to install than other sprinkler systems	Higher operating costs; evaporation and wind-related issues.
Micro-irrigation	Efficient water management; Potential for repeated applications	Higher initial investment; need for filtering and treatment of dirty water.

Source: Own calculations based on food and agriculture organization data

Table 2: irrigation systems' advantages and disadvantages.

Requirement of irrigation scheduling

Irrigation scheduling is a crucial method used by farmers to determine the frequency and duration of crop watering (Isern et al., 2012). It aims to improve irrigation efficiency by providing the right amount of water to restore soil moisture. Monitoring indications are used to determine the necessity of irrigation. Precision water application is essential for optimal effectiveness. Excess or insufficient irrigation can lower crop yields, drain nutrients, wastewater, energy, and labor, and reduce soil aeration. Therefore, precise water application is crucial for effective irrigation management (Nasrullah et al., 2023). Several advantages of irrigation scheduling:

- Farmers can optimize crop yields by arranging water rotation across different fields to reduce crop water stress.
- Maximize soil moisture storage by reducing the number of irrigations needed and the labor and water costs for the farmer.
- The amount of fertilizer required is reduced by reducing surface runoff and deep percolation (leaching).
- Improve agricultural quality and productivity, which increases net returns.
- It helps to control salt problems in the root zone through controlled leaching.

Different crop's water requirements and features

The different water requirements of cash crops and their characteristics are discussed below in Table 3. Crop irrigation water requirements refer to the difference between a crop's actual water requirement and the portion of rainfall it can utilize. The amount of water required for each crop cultivated under irrigation is calculated monthly, often in millimeters of water layer per time unit (mm/month). Crop water demand depends on factors such as crop type, climate, irrigation, rainfall, and growth stage. Crops such as rice and sugarcane require more water than beans or wheat, while sunny, hot climates require more water daily. Fully grown crops require more water than newly planted ones (Darouich et al., 2022)

Crop	Sawing Time	Height	Soil Type	Temperature	PH Level	Irrigation	Rainfall
Wheat	Oct-Dec (90-180 day)	80-120cm	Loam, Clay Loam	18°C - 26°C	6.0 to 7.0 ph	4-5 irrigations 1st-20-25 days, 2nd 40-45 days, 3rd 60-65 days, 4th 80-85 days, 5th 100-105 days, 6th 115-120 days after sawing	20-75 cm
Mustard	Sep-Oct (110-180 days)	160-200 cm	Light to Heavy Loamy	20°C-30°C	6.0 to 7.5 ph	1st pre sawing irrigation, 3 after sawing et 4-week intervals and more depends on rainfall	25-40 cm
Cotton	April-May (150-180 days)	150+ cm	Sandy Loam, Clayey, Loamy Soil	20°C-40°C	6 to 8 ph	4-5 irrigations, depending on rain-fall, 1st irrigation after sawing 4-6 weeks, remaining irrigations at intervals of 3-4 weeks	55-200 cm
Sugarcane	Feb-April (280-360 day)	8- 12+ feet	Well Drained Loamy, Clay Loam, Sandy Loam	18°C-42°C	5 to 8.5 ph	Summer every 15-20 days intervals Winter every20-30 days intervals	75-150 cm
Guar	June-July (60-120 days)	1-2 meter	Drained Sandy Loam	28°C-32°C	7 to 8 ph	Every 20-30 days intervals and de-pends on rainfall.	100-100 cm

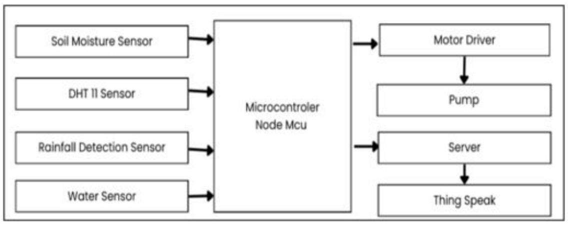
Source: Own calculations based on food and agriculture organization data

Table 3: Different crops water requirements and feature.

Material and methods

System design

The IoT architecture is composed of four layers: the website layer, the management service layer, the gateway and network layer, and the smart device or sensor device layer. Using IoT architecture, we can link the data from soil moisture sensors, rain sensors, water level sensors, and temperature sensors to think speak sever. The Node MCU is connected to various sensors, including soil moisture, temperature, rain detection, water level, and relays, to regulate the motor for optimal field irrigation. The relay is a switch that electromechanically or electronically opens and shuts circuits. The circuit is broken while the switch is open, and the circuit is complete, and the motor operates when it is closed. This switch is controlled with the aid of Node MCU programming. The Node MCU gathers data from all sources and sends it to the thing speak. Programming is done using the Arduino Integrated Development Environment (IDE). The source code editor is included. In this program the gadget using a source code editor, according to our specifications. The programming language is embedded in C. Node MCU is connected with all sensors and sensors are embedded in the agriculture field. Soil moisture sensor measures the soil's moisture content; if it falls below a threshold of 40%, the microcontroller will send a signal to a relay, which will turn on the water motor. If the soil moisture level exceeds the desired level, the microcontroller signals the relay to shut off the motor. If the moisture level is equal to the required threshold, the device will really sit idle and wait for the next signal. To measure the water level of the tank water level sensor is used. Rain detection sensors are used to detect the rain status of the field. If the field is rainy outside, it will send a signal to the microcontroller to indicate the value of 1, if there is no rain outside, then it will send signals 0 to the microcontroller that there is no rain outside in the field. All the sensors are emended in field to detect the real-time field conditions and transfer them to the things speak for real-time monitoring of the sensors value and field conditions. The main block diagram of the system is shown in Figure 2.



Source: Author's work

Figure 2: System block diagram.

System working algorithm

The working of the system is shown in Figure 3:

Step 1: Start the power supply.

Step 2: Analyze the sensor data.

Step 3: The Node MCU esp8266 is used to initialize the system.

Step 4: The Thing Speak application receives updates from the DHT11 sensor, which continuously measures the field temperature and humidity.

Step 5: The field rain condition is continuously detected by the rain detection sensor, which changes the data in the Thing Speak application.

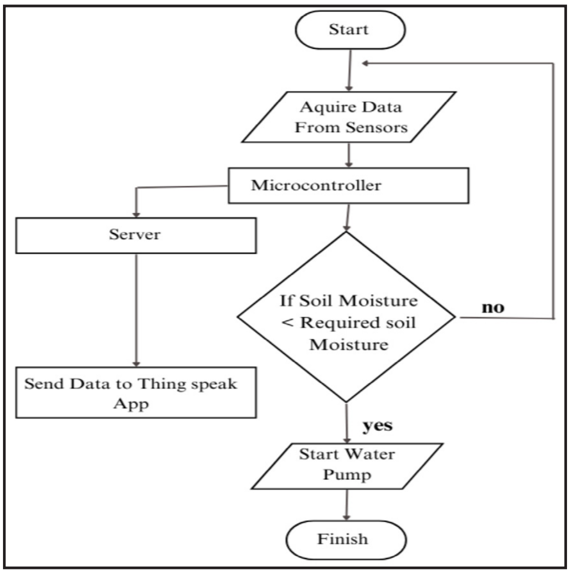
Step 6: The level of the water reservoir is continuously sensed by the water level sensor, which also changes the data in the Thing Speak application.

Step 7: The soil moisture sensor continuously measures soil moisture. If the threshold level of soil moisture is not met, then the motor that is attached to the relay will be switched on, otherwise the system will continuously measure the soil conditions from field.

Step 8: When the amount of soil moisture reaches the necessary level, the relay will automatically turn off the motor.

Step 9: As this is a continuous process, once Step 9 is achieved, the system will again start measuring the field conditions to step 2.

Step 10: This operation will continue until the system's input power is turned off. The flow chart displays both the basic principles of the system and an overview shown in Figure 3.

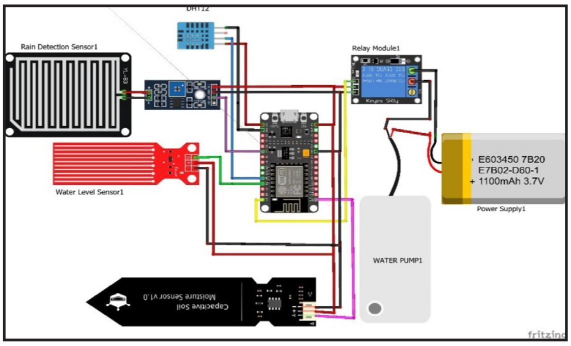


Source: Author's work

Figure 2: System block diagram.

Hardware implementation

An analog pin attached to the YL-69 soil moisture sensor (connected to the node MCU pin A0), a rain detection sensor analog pin connected to the node MCU pin D7, and a breadboard supply power to the DHT11sensors data pin connected to the node MCU pin D4. The Node MCU requires a voltage of 5VDC. Relay modules are required to connect the water pump motor. We will include a transistor to change the relay module's 5V power supply to 3.3V as the ESP8266 requires a 3.3V power source. The transistor is connected to the ESP8266 via a 5k resistor. The relay signal pin is attached to the node MCU D0. An adjustable power supply and a motor pump are attached to the opposite side of the relay. The circuit for the system is shown in Figure 4. The output of the soil sensor at idle is 1023, the highest number, which then eventually drops to zero. Digital readings between 0 and 50 are sent by the temperature sensor. The Node MCU receives data from the sensors and signals from the application, acts on it, and then sends commands to the output pins and updated data to the application. Figure 4 illustrates the hardware connectivity of sensors with the Node MCU.



Source: Author's work

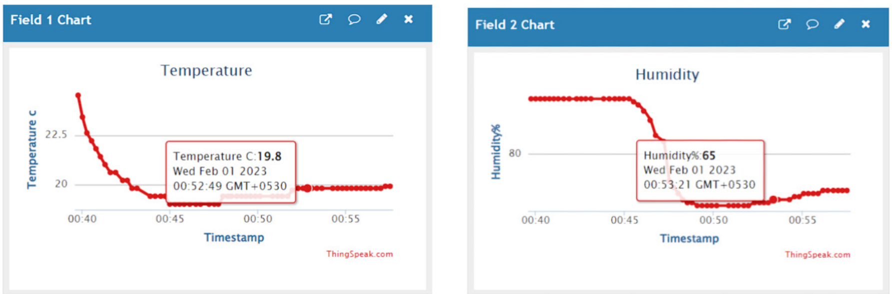
Figure 2: System block diagram.

Result and discussion

The system must first be switched on and connected to Wi- Fi. The functioning of the system will be impacted if the internet connection is ever lost or receives a poor signal. Soil moisture sensor testing is done to monitoring the minute-by-minute variations in the moisture level. The development and testing of automated irrigation system is done successfully. The primary part of hardware in this system is the Node MCU ESP8266 module. All the sensors that are being used to collect data are saved and delivered to thing speak applications for quick and simple evaluations for additional actions and study. A more thorough explanation of each scenario of results is given below.

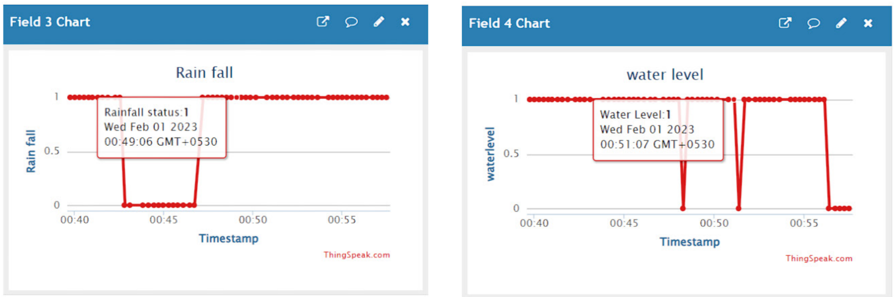
Condition 1: The DHT 11 sensor collects temperature and humidity data from the agriculture field and sends them to the Thing Speak server as shown in Figure 5.

Condition 2: The water level sensor collects the real-time data from the agriculture field reservoir and sends them to the Thing Speak server as shown in Figure 6.



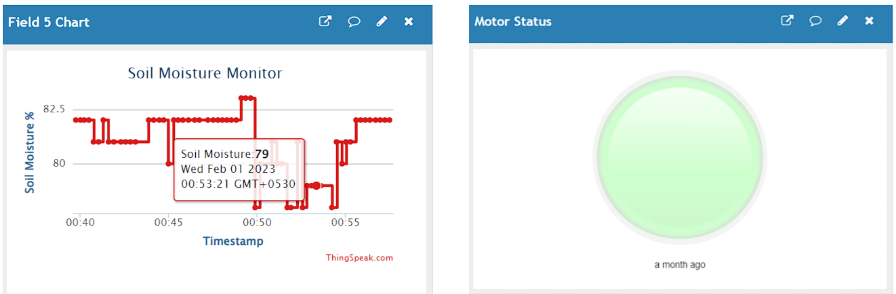
Source: Author's work

Figure 5: Temperature and humidity level status represented on Thing Speak.



Source: Author's work

Figure 6: Water status and rain status represented on Thing Speak.



Source: Author's work

Figure 7: Soil Moisture and Motor Status represented in Thing Speak.

Condition 3: The rain detection sensor collects real-time rain data from the agricultural field and updates the Thing Speak server as shown in Figure 6

Condition 4: soil moisture sensor measure soil moisture from the agriculture filed and send to the Thing Speak server as shown in Figure 7.

Condition 5: If the soil moisture is below the required soil moisture, then the relay sends a signal to activate the irrigation motor, the off state of the motor shown in Figure 7.

Conclusion

Agriculture is an important occupation around the world, with water scarcity being a significant factor. This article discusses various irrigation methods and their efficiency, focusing on crop water. A method using IoT techniques is presented that uses sensor data to communicate with a server via the Internet. A decision support system predicts irrigation needs and triggers relay switches through a web service. Traditional irrigation methods are still used by many farmers, but smart irrigation systems have been developed using a rule-based approach. These systems intelligently decide the need for water and automatically switch on or off the motor, saving time and effort. The system also monitors the status of the water tank and the field rain conditions.

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Volume XVII Number 1, 2025

A Farm-Level Exploration of the Factors Influencing Climate Change Adaptation Strategies among Rice Farmers in Kerala, India

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Abstract

Based on primary data collected through a farm-level survey of 600 households of the major rice-producing districts in the identified agroclimatic zones of Kerala, India, the study employs a multivariate probit model to study the determinants of climate change adaptation strategies of rice farmers. The estimation of the correlation of error terms of selected climate adaptation strategies supports the suitability of multivariate probit model. The results of the model confirm that the farmers' choice of adaptation strategies is significantly affected by factors such as age, gender, level of education, farm size, credit access, reliance on climate information, and access to agricultural extension services. The study further emphasizes the role of institutional factors through government policies such as improving accessibility to affordable credit and provision of reliable climate information, along with effective extension services that enhance the capabilities of farmers enabling them to adopt better climate change adaptation strategies.

Keywords

Climate change, agriculture, adaptation strategies, farm household, multivariate probit model.

Lasithamol, N., Sadath, A. C. and Prasanth, C. (2025) "A Farm-Level Exploration of the Factors Influencing Climate Change Adaptation Strategies among Rice Farmers in Kerala, India", *AGRIS on-line Papers in Economics and Informatics*, Vol. 17, No. 1, pp. 51-66. ISSN 1804-1930. DOI 10.7160/aol.2025.170105.

Introduction

Climate change has become one of the pressing issues faced by the world today due to the alarming levels of its adverse impact on nature as well as socio-economic systems. The impact of climate change has been witnessed in sectors such as agriculture, fisheries, tourism, forestry, and energy (Rao et al., 2019; van Ruijven, 2019; Swami and Parthasarathy, 2020; Yalew, 2020; Shine, 2023). Globally, overall agricultural productivity has slowed down due to climate change, having significant repercussions on food security across the nations (Intergovernmental Panel on Climate Change [IPCC], 2023).

Adaptation to climate change is crucial to protect the livelihoods of those dependent on agriculture. However, perceiving climate change is considered a prerequisite to adaptation, which is followed by planning and decision-making process to adopt from the identified adaptation strategies (Patel et al., 2023). Furthermore, like the impact of climate change, the adaptation strategies of the farmers and their perceptions of climate change are also highly location-specific (Swaminathan and Kesavan, 2012; Reddy et al. 2022).

In India, variability in the climate parameters of monsoon and temperature pose the biggest challenge to agriculture and food security (Swaminathan and Kesavan, 2012; Swami and Parthasarathy, 2020). India's vulnerability to climate change is aggravated due to its relatively higher dependence on agriculture for livelihood (Rao et al., 2019) coupled with the high sensitivity of rice to climate change leading to declined production and productivity of rice in comparison to the growing rate of population (Swain and Thomas, 2010).

Kerala, the 'gateway of monsoon' to India, has witnessed an increase in the frequency of extreme climate events such as floods, landslides, decreased rainfall leading to drought-like situations, water scarcity, cyclones, and extreme changes in temperature in recent years. The floods and landslides of 2018 and 2019 were stark reminders of Kerala's increasing vulnerability to climate change which led to enormous crop and yield losses, adversely affecting the agriculture sector (Rajiv Gandhi Institute of Development Studies, 2018; Kerala State Planning Board, 2021).

Rice cultivation and climate change

Rice (Oryza sativa) assumes large significance in developing regions of the world, more specifically in the Asian continent, where it has been the principal crop for over 2,000 years (Connor et al., 2023). The importance of rice crop in India, and the changing climatic conditions have garnered interest in the scientific and economic assessment of the impact of climate change on rice in India (see Auffhammer et al., 2012; Gupta et al., 2014; Varghese et al., 2020; Aswathi et al., 2022; Dhanya and Jayarajan, 2023; Joseph et al., 2023).

Rice is considered as the staple food of Kerala, and its cultivation assumes significance in the agricultural profile of Kerala. Paddy is cultivated across all the districts of Kerala as it is the principal crop that falls under the category of food grains in Kerala. It is cultivated in all three seasons across all districts of Kerala, except Wayanad where there is no autumn cultivation (Government of Kerala, 2022).

Recent studies in the context of rice cultivation in Kerala have highlighted the vulnerability of rice to climate change impacting its yield, and therefore, suggest the importance of suitable adaptation strategies to reduce the yield loss (Varghese et al., 2020; Aswathi et al., 2022; Dhanya and Jayarajan, 2023; Directorate of Environment and Climate Change, 2022). Foreseeing the adverse impact of climate change on rice production in Kerala, adopting viable strategies becomes a necessity (Swaminathan and Kesavan, 2012; Varghese et al., 2020).

The present study attempts to understand the determinants of the adaptation strategies adopted by farmers to cope with climate change. This would help in evolving policies by taking cognizance of the farm-level experience in enhancing the adaptive capacities of the farmers concerning the impending impact of climate change.

Description of the study area

The geographical location of Kerala lies between 8°18' and 12°48' N latitude and 74°52' and 77°22' E longitude, encompassing an area of 38,863 sq km (38,86,287 ha) in the southwestern part of India. Based on climate, geomorphology, land use, and soil variability, Kerala is delineated into five agroecological zones (AEZ) and twenty-three agroecological units (AEU) (Kerala Agricultural University, 2020). The five agroecological zones are Coastal Plains, Midland Laterites, Foot Hills, High Hills, and Palakkad Plains, while the twenty-three agroecological are delineated considering panchayats as the primary unit. The geographical diversity of Kerala implies diversity in climate across the State. The plains are characterised by a hot and humid climate, while the high ranges have a cool climate.

Materials and methods

Adaptation strategies help minimise the exposure risk of farmers to climate change through a reduction in the marginal impact of climate change on productivity (Mulwa et al., 2017). When faced with adverse climate conditions, farmers may resort to more than one adaptation strategy to ameliorate the adverse impact rather than resort to a single strategy (Ojo and Baiyegunhi, 2018). From the farmer's perspective, a particular climate adaptation strategy is adopted if the expected benefits of adopting a particular strategy are greater than not adopting the strategy.

Multivariate Probit Model

Following Chib and Greenberg (1998) a multivariate model is formulated such that:

$$Y_{ij}^{*} = X'_{ij}\beta_j + \varepsilon_{ij} \quad j = 1, 2, \ldots, m \qquad (1)$$

$$Y_{ij} = \begin{cases} 1 \; if \; Y_{ij}^{*} > 0 \\ 0 \; if \; Y_{ij}^{*} < 0 \end{cases} \qquad (2)$$

Where, Y_{ij}^{*} is the latent variable that captures the unobserved factors and the observed choices associated with ith farm household adapting to jth adaptation strategy. Y_{ij} represents the binary dependent variables of different climate adaptation strategies used by the farm households, and X_i represents the vector of explanatory variables consisting of observed farm characteristics, household characteristics, etc. β_j is the vector of parameters to be estimated, and ε_{ij} is the error term following the normal distribution. Here, the farm households choose to adopt a particular adaptation strategy if the expected output is greater than zero ($Y_{ij}^{*} > 0$) and do not adopt, if otherwise ($Y_{ij}^{*} < 0$).

Multivariate probit model allows for the correlation between unobserved disturbances and the relationship between alternative adaptation strategies. The correlation could arise from either substitutability (negative correlation) or complementarities (positive correlation) among the adaptation strategies adopted by the farm households, the failure to capture which may lead to biased and inefficient estimates (Bahinipati and Venkatachalam, 2015; Mulwa et al., 2017; Regmi et al., 2023). However, with the possibility of jointly adopting more than one adaptation strategy, εij jointly follows multivariate normal (MVN) distribution, where the conditional mean is zero and the variance is one; $\varepsilon_{ij} \sim N\,(0, \omega)$. The resulting covariance matrix is expressed as follows:

$$\omega = \begin{bmatrix} 1 & \rho_{12} & \cdots & \rho_{1m} \\ \rho_{21} & 1 & \cdots & \rho_{2m} \\ \vdots & \vdots & 1 & \vdots \\ \rho_{m1} & \rho_{m2} & \cdots & 1 \end{bmatrix}, \qquad (3)$$

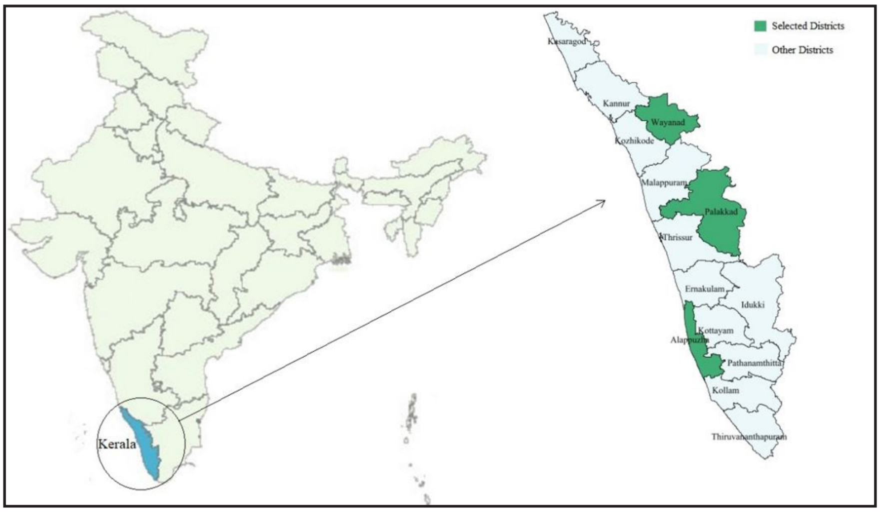
where, ρ denotes the unobserved correlation between the stochastic components of the error terms with regard to any two of the adoption equations estimated in the model. The off-diagonal elements represent the correlation between the stochastic components of different adaptation strategies. If the correlation of error terms in the off-diagonal elements are non-zero, then Equation 1 becomes a multivariate model indicating joint adoption of adaptation strategies. The study uses Stata 17 software to analyse the data.

Sampling and data collection

Primary data for the study was collected through questionnaires and focus group discussions (FGDs). The household survey questionnaire was designed to collect both qualitative and quantitative information regarding the socio-economic and demographic characteristics of households, farm characteristics, farmers' perceptions of climate change and their adaptation practices. Since the study relies on cross-sectional data collected through a survey of household farms in selected districts of Kerala, a multistage sampling method was deployed to select the sample households.

At first, out of the five agro-ecological zones of Kerala, the zones of Coastal Plain, Palakkad Plain and the High Hills were identified based on higher rice production and vulnerability to climate change, from which the major rice-producing districts of Alappuzha, Palakkad, and Wayanad respectively were selected (see Figure 1).

Kuttanad region of Alappuzha district being site designated under the Ramsar Convention, assumes international importance. The system of agriculture in Kuttanad is unique as the cultivation of rice is done below sea level in Kayals which are wetland rice fields created by pumping out water. Palakkad is known as the 'Rice bowl of Kerala' having the largest area of rice cultivation in Kerala. Wayanad district is identified as an ecologically sensitive area falling under the Western Ghats which is a geomorphic feature of immense global importance according to the UNESCO World Heritage Convention. While Palakkad and Alappuzha districts are the largest producers of rice in Kerala, Wayanad is known for the cultivation of numerous traditional varieties of paddy (see Rasheed et al., 2021a). After



Source: Constructed by authors using QGIS 3.28

Figure 1: Map of the study area.

randomly selecting the blocks of the three districts, panchayats to be surveyed from each district were selected. The details of padasekhara samithis (farmer organisations) were collected from Krishi Bhavans or agricultural offices to select the farm households to be surveyed. Padasekhara samithis were the points of contact for the interaction and discussion with farmers for the collection of data. Padasekhara samithis were also contacted to conduct focus group discussions (FGDs).

The sample size was calculated using Raosoft sample size calculator in which the sample size *n* and margin of error *E* are presented as:

$$x = Z(\frac{c}{100})^2 \times r(100 - r) \quad (4)$$

$$n = N\,x\,/((N-1)E^2 + x) \quad (5)$$

$$E = \sqrt{[(N-n)x/n(N-1)]} \quad (6)$$

where, *N* signifies the population size, *r* is the fraction of responses that the researcher is interested in, and *Z*(*c*/100) is the critical value for the confidence level *c*. Applying this formula, the sample size of 200 farm households from each agro-climatic region was arrived at, aggregating to a total sample size of 600 farm households.

Description of variables

Both the dependent and independent variables used in this study were identified based on the empirical literature, discussions with the farm households and the availability of data.

Dependent variables

Adaptation strategies found in the literature and information obtained through the FGDs were used to arrive at the adaptation strategies practiced in the study area. The dependent variables used in the empirical estimation of this study constitute the adaptation strategies adopted by the farmers. The dependent variable of each adaptation strategy used in the multivariate probit model was generated as a dummy variable by assigning the value of 1 if the farmer adopted the particular strategy and the value of 0, if otherwise (Table 1).

The farmers were asked about their perceptions and experiences regarding the changes in climate over the previous years, and the adaptation strategies they practiced to cope with the changing climate conditions. Adaptation strategies employed by farmers to combat climate change include expanding irrigation, bund cropping, use of climate-resilient crop varieties, integration of livestock, shifting to non-farm activities, resorting to crop insurance, and adopting crop calendars. While most of the strategies were consistent with the adaptation strategies discussed in the literature, practices such as bund cropping and use of crop calendars found very little reference in the existing literature. Bunds refer to linear structures in the form of earthen mounds that divide rice fields and enable control of the water depth in the rice fields (Kumalasari and Bergmeier, 2014; Ali et al., 2019; Sattler et al., 2021). Planting vegetables or flowering plants on the bunds enables additional income as well as additional food for household consumption (Nguyen-Van-Hung et al., 2023).

Independent variables

The independent variables used in the study include various determinants of climate change discussed in the reviewed empirical literature, FGDs,

Dependent variables	Description of Variables	Source
Expanding Irrigation	1, if adopted expansion of irrigation, 0 otherwise.	Hassan and Nhemachena, 2008; Abid et al., 2015; Jha and Gupta, 2021; Patel et al., 2023
Bund Cropping	1, if adopted bund cropping, 0 otherwise.	Kumalasari and Bergmeier, 2014; Ali et al., 2019; Sattler et al., 2021; Nguyen-Van-Hung et al., 2023
Climate-resilient Crops	1, if adopted high climate-resilient crops, 0 otherwise	Deressa et al., 2009; Abid et al., 2015; Jha and Gupta, 2021; Dhanya and Jayarajan, 2023; Patel et al., 2023
Livestock	1, if adopted practice of livestock rearing, 0 otherwise	Hassan and Nhemachena, 2008; Nhemachena et al., 2014; Patel et al., 2023
Non-farm Activities	Shifting from farm to non-farm activities involving non-climate sensitive activities. 1, if engaged in non-farm activities, 0 otherwise	Jha and Gupta, 2021; Patel et al., 2023
Crop Insurance	1, if adopted crop insurance, 0 otherwise	Jha and Gupta, 2021; Dhanya et al., 2022
Crop Calendar	1, if adopted crop calendar, 0 otherwise	Wang et al., 2022

Source: Constructed by authors

Table 1: Description of dependent variables.

and discussions with farmers. The determinants include age (Hassan and Nhemachena, 2008; Abid et al., 2015; Megersa et al., 2022), gender (Funk et al., 2020), level of education (Teklewold et al., 2013), household size (Bahinipati and Venkatachalam, 2015; Destaw and Fenta, 2021), dependency ratio (Ingham et al., 2009; Jha and Gupta, 2021), farm size (Deressa et al., 2009), off-farm income (Vo et al., 2021), experience (Nhemachena et al., 2014), .access to credit facilities (Pattanayak et al., 2003; Khanal et al., 2018; Belay et al., 2022), and access to agricultural extension services (Asrat and Simane, 2018; Tesfaye and Nayak, 2022). Based on the FGDs, crop loss due to climate change and reduced cultivation season are included as independent variables.

In the Indian context, to understand the influence of socioeconomic status on the adaptation decisions of farmers, caste is used as an independent variable (Patil et al., 2018). The categories of caste include General, Other Backward Classes (OBC), Scheduled Caste (SC), and Scheduled Tribes (ST).

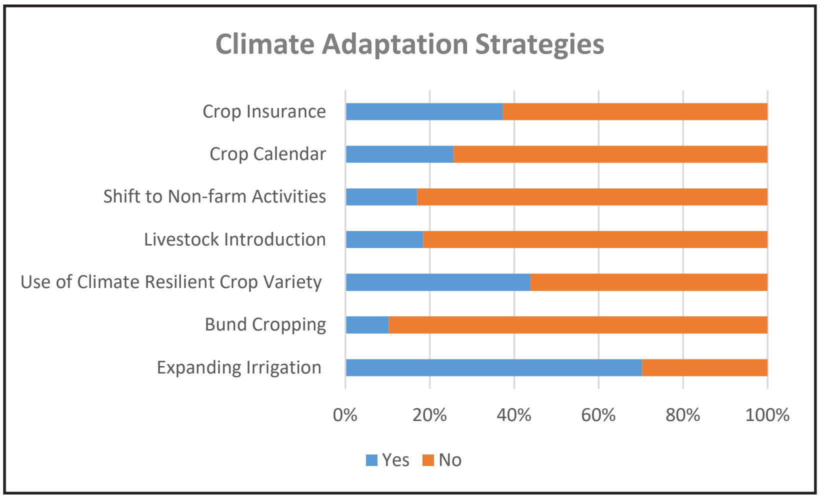
In the survey conducted, it was found that even though farmers had access to climate information through television, radio, etc., elderly farmers relied on their personal intuition in making decisions on farming. Therefore, the independent variable is taken as reliance on climate information, if the farmer chooses to rely on climate information rather than their personal intuition. Additionally, crop loss experienced by the farmers and reduced cultivation seasons were included as independent variables in this study since it was found to be an important variable in determining the choice of adaptation strategies as revealed by the survey. When a farmer experiences crop loss, he becomes more prepared in the future to deal with such exigencies by resorting to adaptation strategies. When farmers perceive any change in climate that would adversely impact their crops, they reduce cultivation during some seasons. Farmers who used to cultivate in three seasons a year had reduced cultivation to one or two seasons a year to reduce the incurrence of loss caused by climate change.

Perception of climate change is an important determinant of climate change adaptation decisions (Hassan and Nhemachena, 2008). While an increase in rainfall was associated with a greater incidence of floods, a prolonged decrease in rainfall was associated with reduced water availability and drought. Hence, both of these perceptions on change in rainfall had a significant influence on the adoption of climate change adaptation strategies (Ojo and Baiyegunhi, 2020). In the present study, the explanatory variables concerning the perception of climate change include the perception of an increase and decrease in annual rainfall received.

Results and discussion

Summary of choice of adaptation strategies

Figure 2 provides the summary of climate adaptation strategies adopted by farmers in terms of percentage. In the study area, majority of farm households (about 70 percent) resorted to expansion of irrigation as an adaptation strategy



Source: Calculated from the primary survey

Figure 2: Summary of climate adaptation strategies adopted by farmers.

to cope with climate change (with farmers cultivating in the Kayals of Kuttanad being an exception). Therefore, it could be inferred from the data that a high proportion of the farm households accorded high importance to expansion of irrigation as an adaptation strategy.

About 43 percent of the farm households switched to climate-resilient varieties of crops as an adaptation measure. While about 26 percent of the respondents resorted to the use of crop calendars, about 37 percent of farmers used insurance as a strategy to cope with climate change. Integration of livestock in the farming system and shifting to non-farm activities were considered adaptation measures by about 19 and 17 percentage of respondents respectively. Even though bund cropping was still practiced by about 10 percent of the surveyed farm households, their biggest challenge was wildlife crop raiding especially by wild boars, peacocks, and monkeys. Therefore, many farmers had to discontinue the strategy of bund cropping which they had practiced in the past as an effective adaptation measure to cope with climate change as well as during pest infestation in the main crop.

Descriptive statistics of independent variables

The average age of the sampled households was 57.34 years, indicating a higher composition of older-generation farmers than the younger generation (see Appendix). The farm-level survey revealed that the farmers were generally older, largely because younger generations are hesitant to take up farming as a primary occupation due to reduced returns, increased cultivation expenses, and the unpredictability of climate conditions. The gender profile reveals that only 13 percent of the sampled households were female-headed, while the majority of 87 percent were male-headed. The average farm size of the households surveyed was 1.13 hectares. The education level of the farmers on average was 10 years. While 80 percent of the farmers faced crop loss due to climate change, 92 percent of the farmers had reduced cultivation seasons.

The field survey revealed that the farmers perceived changes in the timing of monsoons and the nature of accompanying rainfall over the years, while the farmers in all the three regions perceived an increase in temperature over the years. Further, the farmers of the Kuttanad region perceived an increase in rainfall and experienced floods, while the farmers of Palakkad district perceived a decrease in annual rainfall and experienced droughts.

Correlation matrix of choice of adaptation strategies

The estimation results of the multivariate probit model show that the likelihood ratio test Chi^2 (21) = 45.63 with p > 0.0014 signifies acceptance of alternative hypothesis of the mutual interdependence of the error term of the different adaptation strategies (Table 2).

The adoption of insurance as a strategy was found to have significant negative correlation with non-farm activities and bund cropping. It could be inferred that the farmer would either choose crop insurance or engage in non-farm activities. A significant negative correlation was found to exist between non-farm activities and livestock as well as non-farm activities and the use of crop calendars, indicating substitutability among the adaptation choices. Further, it is also seen that a significant positive correlation exists between bund cropping and livestock indicating complementarities between the two strategies. Similarly, the strategies of using crop calendars and the use of climate-resilient crops exhibit complementarity, where the farmer uses both strategies together in combating climate change. The likelihood ratio test of the null hypothesis of interdependence between the adaptation strategies is rejected at 5% level of significance. The estimation of the correlation of error terms of selected climate adaptation strategies supports the suitability of multivariate probit model. The statistically significant pair-wise correlation coefficients of the error terms indicate correlation among the residuals of multiple climate adaptation strategies.

The determinants of climate adaptation strategies by the farmers are given in Table 3. The Wald test given by Wald chi^2 (128) = 883.07 and Prob > chi^2 = 0.0000 is highly significant indicating that the model is a good fit where the subsets of the coefficients of the model is jointly significant and the explanatory powers of the adaptation strategies are robust.

Correlation Pairs	Coefficients	Standard error
Non-farm Activities and Expanding Irrigation	0.0395	0.1395
Crop Insurance and Expanding Irrigation	0.0031	0.1092
Livestock and Expanding Irrigation	-0.1179	0.1308
Climate-resilient Crop and Expanding Irrigation	-0.1521	0.1253
Bund cropping and Expanding Irrigation	0.0372	0.1207
Crop Calendar and Expanding Irrigation	-0.1445	0.1462
Crop Insurance and Non-farm Activities	-0.2655***	0.1081
Livestock and Non-farm Activities	-0.2845***	0.0889
Climate-resilient Crop and Non-farm Activities	0.0006	0.0984
Bund cropping and Non-farm Activities	-0.0123	0.1069
Crop Calendar and Non-farm Activities	-0.5019***	0.1474
Livestock and Crop Insurance	-0.0575	0.0977
Climate-resilient Crop and Insurance	-0.1002	0.1121
Bund cropping and Crop Insurance	-0.2507**	0.1047
Crop Calendar and Crop Insurance	0.2221	0.1396
Climate-resilient Crop and Livestock	0.0788	0.0987
Bund cropping and Livestock	0.2098**	0.1015
Crop Calendar and Livestock	0.1788	0.1902
Bund cropping and Climate-resilient Crop	-0.0682	0.1085
Crop Calendar and Climate-resilient Crop	0.3173**	0.1304
Crop Calendar and Bund cropping	-0.0882	0.1267
Likelihood ratio test of rho21 = rho31 = rho41 = rho51 = rho61 = rho71 = rho32 = rho42 = rho52 = rho62 = rho72 = rho43 = rho53 = rho63 = rho73 = rho54 = rho64 = rho74 = rho65 = rho75 = rho76 = 0: chi2(21) = 45.63. Prob > chi2 = 0.0014		

Note: ***, **, and * indicate levels of significance at $p < 0.01$, $p < 0.05$, and $p < 0.1$ respectively
Source: Calculated from the primary survey

Table 2: Correlation coefficients of selected climate adaptation strategies (from the Multivariate Probit Estimation).

Adaptation Strategy	Expanding Irrigation	Bund Cropping	Climate-resilient Crops	Livestock	Non-farm Activities	Crop Insurance	Crop Calendar
Age	-0.0233	0.0256	-0.0609***	-0.0266*	-0.0357**	-0.0590***	-0.0517**
Gender	-0.4364	0.7137**	-0.5215**	-0.5964***	-0.2266	-0.0104	0.2693
Caste: OBC	-0.2209	-0.1226	-0.3671**	0.3714**	-0.1388	0.0896	0.135
SC	-0.2448	0.2145	0.4184	0.5988**	-0.4077	-0.2861	0.8026*
ST	3.8232	0.2212	-5.7496	-5.1078	-5.4371	-4.2463	-3.7743
Education (in years)	-0.1091*	0.0138	0.0243	0.024	-0.0387	0.1018**	0.1460**
Household Size	-0.1547*	0.0689	0.1131	0.1849***	-0.1694**	0.0223	-0.0923
Dependency Ratio	-0.8149	-0.4913	-0.7112	0.9799*	-0.247	-1.2532**	-1.0452
Experience	-0.0103	-0.0006	0.017	0.007	0.0093	0.0049	-0.0073
Farm Size (in hectares)	0.0173	0.3354***	0.0436	0.2574***	0.5391*	1.0276***	0.4781***
Off-farm Income	-0.0377	0.2119	-0.1694	-0.174	0.0557	-0.1527	1.1945***
Access to Agricultural extension Services	0.4116*	-0.0507	0.2864	0.4079**	0.0987	-0.171	-0.5335**
Ease of Agricultural Credit Access	0.7246***	-0.2862	-0.3101	-0.2687	0.0867	-0.0339	-0.4837*
Climate Information Access	-0.1436	0.4509**	-0.0451	0.2962	0.2205	0.1877	-0.2036
Crop Loss due to Climate Change	-0.1624	-0.1948	0.2238	-0.1705	-0.0272	0.6041***	-0.1154
Reduced Cultivation Season	0.0611	0.6793*	0.0972	0.2634	-0.1288	-0.5796*	0.2922
Perception of Increase in Rainfall	-2.6731***	-1.2148***	3.0853***	-1.2976***	-6.5408	1.0202***	2.6383***
Perception of Decrease in Rainfall	0.3664	-0.4285**	0.0429	-0.0421	0.1932	-1.1382***	-1.2005**
Constant	5.9760***	-4.0277***	2.0528	-1.2496	1.9469	1.3890	-0.4867

Note: ***, **, and * indicate levels of significance at $p < 0.01$, $p < 0.05$, and $p < 0.1$ respectively
Source: Calculated from the primary survey

Table 3: determinants of climate adaptation strategies by the farmers using multivariate probit model.

Expanding irrigation

Expansion of irrigation was adopted primarily in the regions of Palakkad Plain and the High Hills. The results revealed that a lower level of education meant an increase in the probability of expansion of irrigation by 0.02, implying that lesser-educated farmers were more likely to adopt the strategy of expanding irrigation. However, it is to be noted that the farmers on average had 10 years of education, indicating a higher literacy level. Less educated farmers include mainly aged farmers who rely on traditional farming practices and irrigation. Further, it was found that the ease of availing agricultural credit substantially increases the likelihood of the adopting the strategy of expanding irrigation by 0.72. Farm households with better access to credit were more likely to make decisions on adopting adaptation strategies as it provided them relief from various financial constraints (Deressa et al., 2009; Pattanayak et al., 2003; Khanal et al., 2018; Belay et al., 2022). The field survey reveals that out of the total agricultural credit availed, about 5 per cent had been incurred for the purchase of pump sets and enhancement of other irrigation facilities. Very often the farmers had to make a trade-off between utilising the agricultural credit towards financing either new cultivation or any other specific investment requirement such as irrigation indicating that credit facilities were a means of limited finance.

Access to agricultural extension services significantly boosted the likelihood of adopting the strategy of expansion of irrigation (by 0.41) since they are an important source of information on both agronomic services and climate as stated in the existing literature (Hassan and Nhemachena, 2008; Asrat and Simane, 2018). Further, the results reveal that farmers would not think of expanding irrigation if they perceived an increase in rainfall.

Bund cropping

Bund cropping in in the study regions was practiced mostly in the Palakkad Plain, even though the practice was adopted less in the High Hills. Age endows the farmer with experience that helps in better assessment of risks (Megersa et al., 2022). Farmers are keen observers of the changes in climate and make decisions based on their past experiences (Mahmood et al., 2021). Further, the results show that male headed households have a higher probability of resorting to the strategy of bund cropping as revealed by the coefficient of 0.71 at 5 per cent level of significance. Existing literature associates the increased probability of adaptation with higher off-farm income as it empowers the farmer to consider even costlier options of adaptation measures (Deressa et al., 2009; Vo et al., 2021). Additionally, the farm size positively determined the adoption of bund cropping signifying that households with larger farm sizes had higher likelihood of adopting the strategy (by 0.34). Access to climate information increased the probability of adopting bund cropping. This could be because reliability of climate information enables the farmers to make informed decisions on the crop to be cultivated on the bunds. It is further seen that a reduction in cultivation season significantly increases the probability of adopting bund cropping (by 0.68) as it implies making up for the reduction in revenue for the farmers. However, it is observed from the field survey that most of the farmers practiced bund cropping for consumption within the household rather than for commercial purposes. The perception of both increased and decreased rainfall negatively influenced the adoption of bund cropping. From the field survey, it has been observed that the practice of bund cropping has been discontinued by a few farmers in recent times due to increased instances of animal crop-raiding by mainly wild boars, monkeys, and peacocks.

Climate-resilient crops

The rice varieties generally used by farmers were Uma, Jyothy, Jaya, etc. based on the duration of cultivation, high productivity, resistance to pests, and better resistance to warmer temperatures (Dhanya and Jayarajan, 2023). Traditional varieties of rice are also cultivated due to its agro-climatic suitability, affordability due to its low input-intensive nature, and resilience especially under changing climate conditions (Rasheed et al., 2021b). The cultivation of traditional varieties of rice such as Veliyan, Thondi, Jeerakasala, Gandhakasala, etc., was prevalent in the High Hill region of Wayanad district.

The use of climate-resilient varieties of crops was influenced by age and gender negatively, indicating a higher likelihood of adoption by younger farmers (by 0.06) and female-headed households (by 0.52). The empirical literature points out the varying impact of age on a farmer's decision to adapt. The younger farmers are expected to have a longer horizon of planning and are capable of undertaking long-term adaptation measures such as irrigation or adopting a mixture of crop-livestock strategies (Hassan and Nhemachena, 2008). From the field survey, it was observed that the farmers of the Scheduled Tribes or the indigenous community in the High Hill region of Wayanad actively cultivated traditional rice varieties rather than any high-yielding varieties as they felt that these crops were more tolerant to climate change. Further, the result reveals a significant positive influence on the perception of increased rainfall in adopting climate-resilient crop varieties.

Livestock

The strategy of introducing livestock means that even when the main crop does not do well due to climate change, an alternative option exists for the farmers (see Nhemachena et al., 2014). The results reveal that younger generation farmers (by 0.03) and female headed farm households (by 0.60) have an increased probability of integrating livestock with the existing farming system. In comparison to the general category farmers, the farmers belonging to the OBC (by 0.37) and SC (by 0.60) categories significantly increased likelihood of adopting the strategy of livestock introduction to cope with climate change. The size of farm has a significant positive influence on introduction of livestock as indicated by a coefficient of 0.26 at 1% level of significance, corroborating the influence of farm size on adaptation strategies as evinced in the reviewed literature (Asrat and Simane, 2018; Aryal et al., 2020). A high dependency ratio indicates higher dependency burden on the working population due to increased responsibility to feed the dependents and larger expenditure (Ingham et al., 2009; Jha and Gupta, 2021). Larger household size indicating availability of larger manpower on the farm influences the introduction of livestock into the farming system, which is in agreement with the results of Funk et al. (2020). Due to the higher labour endowment associated with larger household size, many empirical studies have found household size to be a positive determinant of adaptation decision (Abid et al., 2015; Destaw and Fenta, 2021; Megersa et al., 2022). Further, the perception of increased rainfall is found to have a significant negative impact on introducing livestock.

Non-farm activities

Lower age and smaller household size significantly increased the probability of making adaptation decision of diversification from farming to non-farm activities to cope with climate change by 0.04 and 0.17 respectively, while larger farm size increased the probability 0.53. Age is found to have a negative relationship with shifting to non-farm activities, indicating the aversion of elderly farmers to digressing from their main occupation of rice cultivation. The results further show that while the larger household size dissuades the farmer from shifting to non-farm activities, the size of the farm exercises a significant positive impact on shifting to non-farm activities. Since farm size indicates the wealth endowment of a farmer, larger farm size is associated with an increased capacity of the farmer to adopt adaptation strategies (Deressa et al., 2009). In other words, a larger farm size enables the farmer to diversify to other activities to minimize risk of climate change.

Crop insurance

Younger farmers exhibit a greater likelihood of resorting to insurance as an adaptation strategy as indicated by the negative coefficient of 0.06 at 5% level of significance. It is observed that the higher education level of the farmer increases the probability of the farmer adopting crop insurance by 0.10. The education level of farmers plays an important role in their understanding of the risks associated with climate change, and access to scientific information, enabling the farmer to plan and make decisions on suitable adaptation strategies to be implemented to reduce the risks arising thereon (Aryal et al., 2020; Mahmood et al., 2021; Destaw and Fenta, 2021). If the dependency ratio is higher, it is less likely that the farmer would adopt crop insurance. Larger farm size increased the probability of resorting to crop insurance. The results further show that the past experience of crop loss due to climate change significantly increased the probability of resorting to crop insurance as indicated by the coefficient of 0.60. The cost of cultivation incurred could be high for the farm households having larger farms, and therefore they resort to crop insurance to make good the loss in the case of extreme climate events. Farmers resorting to crop insurance due to past experience of crop loss is indicative of the fact that they anticipate the occurrence of extreme climate events which are likely to reduce their farm income. Reduced crop cultivation and the perception of a decrease in rainfall have a significantly negative impact on the adoption of crop insurance. The perception of higher rainfall positively influences the adaptation choice of resorting to crop insurance.

Furthermore, it is observed that all farmers do not adopt the strategy of crop insurance due to issues confronting availing claims during crop loss. From the policy perspective, an increase in the number of weather stations or observatories would help in improving the real-time monitoring of weather parameters. These would act as stations for recording proximate weather parameters during the event of crop loss which increases the farmers' chance of availing insurance claims. An increase in the number of claims would encourage more farmers to adopt the strategy of crop insurance.

Crop calendar

The younger generation of farmers have a higher probability of resorting to crop calendars as an adaptation strategy towards coping with climate change as indicated by the coefficient of 0.05 at 5% level of significance. The farmers opine that crop calendars would also bring uniformity in the cultivation and harvesting of crops, enabling even farmers with small and fragmented landholdings to reap the economies of cultivating together. The education level, and farm size significantly increase the probability of the use of crop calendars by 0.15 and 0.48 respectively. The results reveal that as the access to agricultural extension services and agricultural credit diminishes, the probability of adopting the strategy of crop calendars increased by 0.53 and 0.48 respectively. Further, if the farmers perceive an increase in rainfall they are more likely to opt for the use of crop calendars, while they are less likely to prefer crop calendars if they perceive decreased rainfall. However, it is to be noted that the crop calendars need to be prepared for each agro-ecological zone or unit with utmost care by the government entities operating at the grass-root level, in consonance with the meteorological department ensuring its reliability for the farmers. However, the development and preparation of crop calendars is an area of study which requires the use of scientific knowledge and technology, coupled with stakeholder deliberations aimed at fostering broader acceptance and adoption by the farmers.

A limitation of this study is that it analyses only the determinants of climate adaptation strategies of three agro-ecological zones of Kerala, while a more comprehensive disaggregate analysis incorporating all AEZs of Kerala that cultivates paddy would provide insights into diverse climate change adaptation strategies followed in each zone enabling tailored policy suggestions for each zone. However, the focus of this study was on the determinants of climate change adaptation strategy among the rice-farmers of Kerala considering the three AEZs together.

Conclusion

Adaptation has become imminent for farmers due to the evident changes in climate, enabling them to secure their livelihood, ensure food security, and earn a better income, which constitutes their primary objective of engaging in farming activity. However, the choice of adaptation strategy employed by the farmer is determined by a multiplicity of factors. This study analysed the determinants of climate change adaptation strategies among the rice farmers of Kerala employing a multivariate probit model. The adaptation strategies and their determinants were identified from the literature and the information collected from the farmers through FGDs. The results revealed both positive and negative correlations among the adaptation strategies employed by the farm households to cope with climate change signifying interdependence among various adaptation strategies, thereby justifying the use of a multivariate probit model in this study. The results of the multivariate probit model further revealed that the farmers' choice of adaptation strategies is majorly determined by the factors, age, farm size, and the perception of increased rainfall.

However, specific policy actions of the government are warranted to make agriculture sustainable for the farmers, by improving their adaptive capacity (Bahinipati and Venkatachalam, 2015). Government policies towards improving access to affordable credit would aid the farmer in adopting better adaptation strategies. The policy of enhancement of easier access to credit facilities especially targeting the expansion of irrigation facilities is required since the credit availed by the farmers is very limited and is spent on other purposes such as cultivation of crops or for the purchase of other inputs, rather than in methods to improve their resilience to climate change. Further, the timely availability of credit with zero or minimal interest rates would encourage more farmers to access affordable financing options. Moreover, it is found that farmers rely on personal intuition rather than the available climate information, even though they have access to it. This is due to the non-reliability of the available climate information. To provide reliable information, government intervention is inevitable especially through investment in research and development to deliver more accurate predictions on climate inputs such as rainfall, temperature, wind, and extreme climatic conditions to the farmers. Furthermore, access to agricultural extension services continues to be an issue that needs to be addressed (as corroborated by Funk et al., 2020) by the government to educate the farmers on government policies and schemes, and also to provide services related to improved production technologies and adaptation strategies. Policies towards increasing the number of weather stations or observatories and usage of kisan drones to assess the crops grown and loss incurred would indirectly incentivise farmers to adopt crop insurance as an adaptation strategy by easing the process of insurance claims and fostering transparency (also suggested by Patel et al., 2023). Additionally, preparation of accurate and reliable crop calendars in consultation with the meteorological department and stakeholders would constitute an inclusive approach towards improving the resilience of the farmers towards climate change. In conclusion, along with the household and socio-economic determinants, institutional support to farmers through appropriate policy measures, enhance their adaptative capabilities to cope with climate change.

Acknowledgments

The authors gratefully acknowledge the University Grants Commission (UGC), Government of India, for the research fellowship received by the first author for her doctoral research at the Central University of Kerala, India.

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Appendix

Independent variables	Data Type	Mean	Std. Dev.
Age	Continuous	57.34	10.67
Gender	Binary (1 = Male, 0 = Female)	0.87	0.33
Caste:			
General	Binary	0.39	0.49
OBC	Binary	0.50	0.50
SC	Binary	0.06	0.24
ST	Binary	0.06	0.23
Education (in years)	Continuous	10.04	3.08
Household Size	Continuous	4.65	1.14
Dependency Ratio	Continuous	0.68	0.15
Experience	Continuous	39.64	14.65
Farm Size (in hectares)	Continuous	1.13	0.92
Non-farm Income	Binary (1 = Yes, 0 = No)	0.72	0.45
Access to Agricultural Extension Services	Binary (1 = Yes, 0 = No)	0.44	0.50
Ease of Access to Agricultural Credit	Binary (1 = Yes, 0 = No)	0.77	0.42
Reliance on Climate Information	Binary (1 = Yes, 0 = No)	0.42	0.49
Crop Loss due to Climate Change	Binary (1 = Yes, 0 = No)	0.80	0.40
Reduced Cultivation Season	Binary (1 = Yes, 0 = No)	0.92	0.28
Perception of Increase in Rainfall	Binary (1 = Yes, 0 = No)	0.34	0.48
Perception of Decrease in Rainfall	Binary (1 = Yes, 0 = No)	0.31	0.46

Source: Calculated from the primary survey

Table A1: Summary statistics of independent variables.

Volume XVII Number 1, 2025

The Approach of Managers to the Internal Control System in Contemporary Agricultural Enterprises in Slovakia

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Abstract

Nowadays, we consider it necessary that the accounting entities are built of high quality, stable, and should be equipped with an internal control system. We consider it important that they base their decisions on their own and up-to-date information and that there is feedback afterwards. In the work, we also focused on the preference for improving the internal control system in selected accounting entities. Preferences were analyzed based on a questionnaire survey of managers and executives in selected accounting entities. The database contains information on 46 respondents from the ranks of managers, financial directors, accountants and other responsible employees for the performance of control from the questionnaire survey. We decided to use the binary logit model in order to estimate the inclination of individual preferences in favor of the need to improve the internal control system. On the basis of which we came up with interesting findings from the point of view of management and executives in selected agricultural enterprises. With our findings from the analysis of managers' preferences, we can state that the decisive factors that contribute to the willingness to improve the internal control system are the automation of control processes. We found that managers who make a decision based on a thorough analysis of the problem contribute to the willingness to improve the internal control system. Managers' satisfaction with financial evaluation was also a decisive factor, and therefore those employees who were satisfied with their financial evaluation were also more willing to improve the internal control system. At the same time, it should be noted that the absence of current scenarios in which activities are developed, along with the need to adequately address constant changes and changes in market requirements, brings a significant change in business management. .

Keywords

Internal control system, accounting, business management, preference analysis.

Látečková, A. and Súlovská, P. (2025) "The Approach of Managers to the Internal Control System in Contemporary Agricultural Enterprises in Slovakia", *AGRIS on-line Papers in Economics and Informatics*, Vol. 17, No. 1, pp. 67-79. ISSN 1804-1930. DOI 10.7160/aol.2025.170106.

Introduction

Internal control is a dynamic and repetitive process that aims to help management focus on the operational and financial goals of the organization. The establishment of a system of internal control provides reasonable assurance regarding the achievement of three objectives: effectiveness and efficiency of operations, reliability of reporting and compliance with applicable laws and regulations (COSO, 2023).

Due to limited archival data, relatively few researchers have empirically examined internal control over operations and compliance. Although researchers do not directly examine operations and compliance objectives, researchers generally suggest a positive relationship between the achievement of the three internal control objectives. For example, Turel and Bart (2014) suggest a positive association between internal control over financial reporting (ICFR) and financial performance (improved performance from lower compliance costs and improved operations). Feng et al. (2024) claim that the quality of financial reporting is also ensured as a result of the operational performance of the accounting entity. Examining the connection between material deficiencies related to the inventory in ICFR and the accounting entity's inventory management, it follows that their study points to a positive connection between the quality of ICFR and the accounting entity. Similarly, Chang et al. (2019) provide systematic evidence of the relationship between effective ICFR and firm operating activity. Kedia and Reddy (2016) also find a significant association between operations that were not aligned with corporate activity and financial misstatement. In addition, a recent study by Abbott et al. (2016) provide evidence that operational control risk indicates potential weaknesses in financial reporting controls. Specifically, Abbott et al. (2016) focused on operational control risk in two ways: data breaches (i.e. computer security attacks) and a control risk index developed through form text analysis. Their findings suggest that operational control proxy risks are positively related to subsequent financial reporting deficiencies, restatements, comments, and audit fees. The organization's plan and all coordinated methods and measures adopted within the enterprise protect its assets, control the accuracy and reliability of its accounting data, promote operational efficiency and promote compliance with the management policies maintained (American Institute of Certified Public Accountants - AICPA). The Turnbull Report, first published in 1999, defined internal control and its scope (AICPA, 2013).

An assessment of the internal control system therefore requires a deep understanding of the firm's business, the risks it faces and the controls it has in place to deal with risk exposure at all relevant organizational levels. This understanding, in turn, means understanding the entity's goals, business processes, organizational resources, structures, roles and responsibilities. The review task is therefore for stakeholders with different professional backgrounds and perspectives on internal control matters, including managers, executives, process owners, risk managers, and internal and external auditors (Elder and Yebba, 2020).

On the basis of the valid legal regulation of businessmen's accounting, it describes the most important controls that the selected accounting entity should carry out in order for its accounting to be correct, complete, demonstrable, and comprehensible. The description of the control of accounting accuracy by the accounting entity itself also draws attention to the objects of the control. The basic task of accounting is to faithfully display, record and report the economic reality of the company.

In terms of content, reliable and correct information is the basis of effective business management, in which the pragmatic side of the company's accounting information is applied. However, not every manager knows how to use them correctly. In order for this information to be truly beneficial, it is essential that managers (Látečková, 2023):

- mastered basic accounting terms and principles,
- were able to correctly interpret the information value of each synthetic account, interrelationships between accounts, options for creating analytical records, the method of creating financial statements and their subsequent analysis.

The method of evaluating the actual performance of the internal control system is directly linked to the evaluation of its design. Indeed, it is not possible to assess the actual effectiveness of the performance of an internal control system without assessing its design (IIA, 2024). Thus, assessing the compliance of internal procedures and external regulation is only a part of evaluating the performance of the internal control system. Furthermore, compliance assessment is only a fraction of the overall assessment of the adequacy of the internal control system. This principle challenges many assumed notions of control. Furthermore, verification regarding the actual functioning of the internal control system is only possible when the design has been assessed and found to be adequate. If not, the verification process should take into account the assessment of the impact of the residual risk resulting from a faulty or insufficient system (Dittmeier, 2014).

The importance of internal control systems in organizations lies in the effective performance of functions and tasks, avoiding surprises, preserving the rights of shareholders, developing the general quality of activity and verifying the appropriateness of this activity, as shareholders always expect the organization to have good and effective control (Hussney, 2022).

An assessment of the internal control system therefore requires a deep understanding of the firm's business, the risks it faces and the controls it has put in place to deal with risk exposure at all relevant organizational levels. This understanding, in turn, means understanding the entity's goals, business processes, organizational resources, structures, roles and responsibilities. Therefore, the review task involves stakeholders with different professional backgrounds and perspectives on internal control matters, including managers, executives, process owners, risk managers, and internal and external auditors (Elder and Yebba, 2020).

Most cases of financial fraud occur in the form of false disclosure of financial statements, which is usually caused by mutual agreement on a false transaction with related parties or by changing the normal and fair price of the transaction, resulting in the transfer of profits and risks. between related parties and heterogeneous disclosure of accounting statements leads to incompatibility or low comparability of accounting information (Li et al., 2022).

Management of enterprises that implement abnormal transactions with related parties use their information advantages to choose accounting policies and disclosure methods that lead to the maximization of their returns, to implement accounting information systems that differ from industry standards, or to manipulate the accounting disclosure process. information, which will reduce the comparability of accounting information with other companies in the industry (Blokdyk, 2020).

Compared with external supervision, internal control as the key to the success of corporate governance can identify various types of related party transactions and limit the scope, frequency and proportion of related party transactions, especially the abnormal related party transactions that Li et al. (2022) in his of studies directed his attention, on the basis of which they effectively affect the authenticity of published financial statements and the comparability of accounting information.

The governance of modern companies is a critical research area for scholars at home and abroad, and principal-agent theory has become a theoretical source and foundation of thought for the study of corporate governance issues. Theoretically, companies have multiple and multi-layered ownership institutions, so the principal-agent problem must deal with incentive incompatibility (Liu et al., 2023). Equity incentives were first introduced in the US to create a risk-benefit sharing mechanism that aligns management interests with shareholder interests (Lisic et al., 2019). Since then, managerial ownership has become an effective measure of corporate incentives in developed markets due to its long-term and effective problem-solving benefits.

Study by Chang et al. (2014), using non-publicly available data obtained from Taiwan's regulatory agency, explores an almost unexplored area of research regarding the disclosure of internal control deficiencies in an entity's operations and compliance. Specifically, we examine whether the size and competence of internal audit influence the quality of internal control over operations and compliance. The results indicate that IA staff size is negatively associated with the occurrence of internal control deficiencies in operations and compliance. In addition, IA staff competence (i.e., collective level of education, professional certifications, and external audit work experience) is negatively associated with internal control deficiencies in compliance, but not in operations. The findings partially support the contention that IA quality is positively associated with the effectiveness of internal control over operations and compliance.

An effective internal control system includes the organizational planning of the enterprise and adopts the entire work system and process to meet the following objectives (Bradley et al., 2017):

- security of business assets against theft and wastage,
- ensuring compliance with business policies and the law of the country,
- evaluating the functions of each employee and officer in order to increase the efficiency of the operation,
- ensuring real and reliable operating data and financial statements.

Accounting entity using information technologies that support the integration and sharing of information have a positive effect on improving the effective functioning of internal control (Chen et al., 2008).

Information integration can reduce data manipulation and errors, improve information accuracy, and ensure effective formulation and implementation of an accounting entity's internal control activities (Teru et al., 2017). Information sharing can improve the availability of information from different departments and facilitate communication within the accounting entity.

We assume that IT expertise can improve the overall quality of the information system. Board directors with IT experience can help with the company's IT principles and architecture and are able to ensure that the organization's IT sustains and extends its strategies and objectives, including IT-related internal control strategies and policies. In addition, when it comes to building an information system, IT expertise can help select the right IT infrastructure, bridging the gap between the system and the actual business needs during system design. (Feng Y., 2024) Finally, directors with IT education are more likely to value the information system, and their appreciation will create a supportive and accepting environment for the information system in the company. Our paper contributes to the literature in the following aspects.

An information attack generally results in confidential data theft, financial fraud, downed web servers, and corrupted operational data, all of which affect the accuracy and reliability of financial data derived from the information system. If entities do not implement proper information security, they cannot guarantee the accuracy and reliability of their financial data. Built-in ERP control functions can positively affect the effectiveness of internal financial reporting controls. However, ERP does not necessarily protect against some deliberate system manipulations, for example, some controls may not be activated in time during the implementation phase. In addition, top managers may try to override some control functions to manipulate the date of performance of revenue management (Chang, 2019).

While many studies have examined IT governance, there remains a significant research gap regarding the link between internal audit (IA) functions, IT governance, and IT controls. Some academic discourses have initiated the investigation of this triadic relationship. For example, Héroux and Fortin (2013) delved into the participation of IA in IT governance, clarifying the role of internal audits within IT governance and the interplay between the distinctive elements of IA and its involvement in IT governance. Their finding points to two characteristic elements of IA that increase IA involvement in IT governance as the extent of IT audit resources and experience and the number of IT staff associated with IT training or certification.

Recent studies have primarily focused on the effects of digital transformation on firm production factors, including cost reduction, human capital improvement, and technological advancement (Cheng et al. 2018).

In their study, Zhang and Dong (2023) state the benefit in two aspects. On the one hand, it shows that the quality of internal control serves as a specific mechanism through which digital transformation affects the productivity of firms. This finding provides valuable insight into the precise mechanisms governing the economic consequences of digitization within firms. On the other hand, this article focuses on China.

While numerous studies evaluate internal audit quality with a focus on ICFR, our study differs from previous research by extending the examination of internal control quality to two critical but less studied objectives—operations and compliance. Specifically, our findings help to bridge a gap in the literature by examining the effects of IAF attributes on the achievement of a company's operational and compliance goals, and expand our understanding of the relationship between IAF and internal control objectives. In addition, the unique data set obtained from the Taiwan Regulatory Authority allows us to avoid some of the shortcomings of previous archival-based papers, which mainly depend on the Global Auditing Information Network (GAIN) database that collects auditors' responses to IIAs. Questionnaires (Wu, 2024).

Ostaev et al. (2022) in their study focus on internal controls in the system of economic security of the agricultural sector. The aim of the study was to establish the function of internal control in the system of economic security of agricultural enterprises, as a mechanism for identifying risks and threats. In accordance with this goal, the main task was determined to justify the theoretical and practical aspects of internal control in the system of economic security of agricultural enterprises. The work examines substantive and formal methodological aspects, including the study of laws, theories, the structure of scientific knowledge, analysis of research methods from the point of view of logical structure and formalized approaches for the construction of theoretical knowledge.

In studies by Kontsevaya S. and Alborov R. (2017) focused on the management system in Russian agricultural enterprises. The aim of the study was to design a system for making managerial decisions and a control system. The proposed system of management decisions is based on the calculation of coefficients identifying economic (gross production, labor productivity, material return, amortization, etc.), environmental (material waste, labor intensity, etc.) and social efficiency (average wage, rates of growth and labor productivity and other) according to the types of products in the agricultural enterprise. Production efficiency is estimated by a system of evaluation criteria and factors. The factors in the proposed system are divided into 3 groups: economic efficiency factors, environmental efficiency factors, social efficiency factors. The system of control and evaluation of the efficiency of agricultural production based on the presented factors is carried out in special tables, where each actual value and each type of product has an efficiency coefficient for the current year in relation to the base value or the average value for the last 3 years. The post contains an example of calculating coefficients based on data from financial accounting.

Managerial accounting would, according to Ostaev et al. (2020) should have been aimed at solving long-term prospective problems. Managers of an economic entity with the authority to make strategic decisions develop forecast scenarios taking into account the opinions of competent experts involved in the assessed economic area. The authors developed a coordinated idea of which option for predicting economic development is the most advantageous for an agricultural enterprise, also from the point of view of the variability of the economic situation. The authors' study was aimed at improving the quality of managerial accounting in agricultural enterprises with a comprehensive evaluation of the effectiveness of activity management.

Materials and methods

The main goal of our study was to find out what factors on the part of managers contribute to the willingness to improve the internal control system. For that reason, we conducted a questionnaire survey. The database contains information on 46 respondents from the ranks of managers, financial directors, accountants and other responsible employees for the performance of control from the questionnaire survey. In the analyzed period of 2023, 15 agricultural enterprises were monitored, in which we tested internal controls. When choosing accounting entities, we chose the following criteria:

- accounting entities have an implemented internal control system,
- accounting entities are focused on primary agricultural production,
- accounting entities account in the double-entry bookkeeping system,
- the managers of the selected companies were willing to provide us with sensitive internal data and cooperation was already established with them in the previous period. In this way, we ensured the availability of relevant data for solving our research.

25 companies were approached, of which 15 companies accounting in the double-entry bookkeeping system expressed their willingness to cooperate in the selected issue.

We obtained the outputs from our analysis from the multi-platform software Gretl.

The estimated model includes the following variables, which we created on the basis of a questionnaire survey:

- PreferenciaVKS – Do you see a need to improve the internal control system? (0-no, 1-yes) This is a dependent variable, the other mentioned variables are exogenous:
- AccountSys - Do you think that the accounting system in your company is effective in terms of control processes?
- Automation - Do you think that the automation of internal control processes will make the performance of the control itself more efficient?
- Personality Types – What type of personality best describes you in your work?
- Time – Are you willing to work overtime, if necessary?
- Self-development – Would you be interested in self-development in your work?
- Salary – Are you satisfied with the amount of your financial evaluation?
- Gender – 0- female, 1- male;
- Age – 0- 30-49 years, 1- 50 and more years;
- Children – 0 - has no child, 1 - at least one child;
- Education – 0-secondary education, 1-university education.

Of the total number of 46 respondents, 21 were women and 25 were men.

Please, abide by the template paper structure, it is obligatory.

The basic characteristics of the basic set of respondents are shown in Table 1.

		gender (in %)	
		woman	man
Personality type	Perceivers	33	28
	Thinkers	48	31
	Judges	19	41
Age	30-49 y.	48	44
	50 and more y.	52	56
Education	Secondary education	38	32
	University	62	68
Children	Have no child	33	20
	Have a child	77	80

Source: Own processing based on data from a questionnaire survey.

Table 1: Basic characteristics of the basic set of respondents.

To develop the work, we decided to use the binary logit model in order to estimate the inclination of individual preferences in favor of the need to improve the internal control system (ICS). We focused on monitoring whether respondents have the willingness and effort to contribute to the improvement of this system. Otherwise, the respondents do not see the need to improve the internal control system, and they consider the current state to be sufficient. We obtained the outputs from our analysis from the multi-platform Gretl software.

For the analysis of preferences regarding the internal control system, it is not necessary to formulate hypotheses, as we focused on analyzing the level of influence of individual exogenous variables on the endogenous variable.

We monitor the binary variable Y_i, which takes on values of 0.1.

Research premise is as follows:

$Y_{it} = 0$ (respondents do not see the need and are not willing to improve VKS), [1]

$Y_{it} = 1$ (respondents see the need and are willing to improve VKS).

Using the defined latent variable Yit and individual exogenous variables Xji, we entered the following equation for the model for the analyzed period:

$$Y_{it} = b_0 + b_1X_{1i} + b_2X_{2i} + b_3X_{3i} + b_4X_{4i} + b_5X_{5i} + b_6X_{6i} + b_7X_{7i} + b_8X_{8i} + b_9X_{9i} + b_{10}X_{10}i + b_{11}D_{1i} + b_{12}D_{2i} + b_{13}D_{3i} + \varepsilon_i \quad [2]$$

We refer to the cross-sectional entity as i, which takes the values $i = 1,...,15$.

Where:

Y_{it}- i-th accounting entity, the t-th period of the endogenous variable "VKS Preference",

X_{1i} - i-th accounting entity of the exogenous variable "AccountSys",

X_{2i} - i-th accounting entity of the exogenous variable "Automat",

X_{3i} - i-th accounting entity of the exogenous variable "Personality Types"

X_{4i} - i-th accounting entity of the exogenous variable "Time",

X_{5i} - i-th accounting entity of the exogenous variable "Self-development",

X_{6i} - i-th accounting entity of the exogenous variable "Salary",

X_{7i} - i-th accounting entity of the exogenous variable "Gender,

X_{8i} - i-th accounting entity of the exogenous variable "Age",

X_{9i} - i-th accounting entity of the exogenous variable "Children",

X_{10i} - i-th accounting entity of the exogenous variable "Education",

D_{1i} - i-th accounting entity of artificial variable "OsobTypyA",

D_{2i} - i-th accounting entity of artificial variable "OsobTypyB",

D_{3i} - i-th accounting entity of artificial variable "OsobTypyC",

b_0 - locating constant,

$b_{1\text{-}13}$ - unknown parameter of the binary logit model,

ε_i - i-th accounting entity of the random error of the variable Y_i.

It was necessary to create three artificial variables so that they take on two states (0-no, 1-yes), which we tested using a binary ligit model:

"PersonTypesA" - perceivers,

"OsobTypyB" - thinkers,

"OsobTypyA" - judges.

For maximum likelihood estimation, we used the works of authors Ajmani and Wooldridge. Who devote more detail to this statistical method in their works. The logit model is based on the maximum likelihood estimation method (Chi-square). In the case of the binary logit model, we will consider it as a distribution function, a logistic distribution function. The estimation of parameters b1-13 is realized using the method of maximum significance of the model, now it is no longer a linear function, where we assume independence of observations. The closer the ratio of the logarithms of the likelihood functions is to 0, the higher the fit rate, on the basis of which we claim that the model is complete and better describes the modeled data (Ajmani, 2009).

Using the odds ratio, we get a better idea of the interpretation of the coefficients in the binary logit model, in which the logarithm of the ratio of the probability of occurrence of the event pi and the probability of the occurrence of the complementary event ($1-p_i$) is defined. We refer to this share as the chance, which is calculated by simply taking the logarithm of the estimated parameters. The odds ratio for the variable X_{ji} was calculated in Excel via the function $\exp(b_j)$. If we get a value greater than 1, we can claim that respondents with a higher education will increase the odds ratio in their willingness to improve the internal control system by the calculated value expressed in %, assuming that all other variables are constant. If we obtain a value of the de-logarithmic coefficient smaller than 1, we claim that respondents with a higher education have a reduced chance ratio in their willingness to pay environmental taxes by the calculated value expressed in %, assuming "Ceteris paribus". The correct interpretation of the model parameters for the binary logit model is very important for the successful implementation of the model (Wooldridge 2002).

Results and discussion

A considerable number of authors deal with the issue of the internal control system. By studying various scientific literary sources, we obtained a comprehensive view of the investigated issue. We consider it important to acquire knowledge, especially in the areas of performance and efficiency of the functioning of the internal control system.

Our finding was that there were not many scientific publications devoted to the need for an internal control system focused on the field of accounting in agricultural enterprises. We obtained the following relevant resources from the authors Ostaev et al., Kontsevaya and Alborov, which are devoted to agricultural enterprises in the field of internal control system. Ostaev et al. (2022) in their study focus on internal controls in the system of economic security of the agricultural sector. The aim of the study was to establish the function of internal control in the system of economic security of agricultural enterprises, as a mechanism for identifying risks and threats. In accordance with this goal, the main task was determined to justify the theoretical and practical aspects of internal control in the system of economic security of agricultural enterprises. The work examines substantive and formal methodological aspects, including the study of laws, theories, the structure of scientific knowledge, the analysis of research methods in terms of logical structure and formalized approaches for the construction of theoretical knowledge.

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Based on the study of domestic and foreign literature, we can conclude that a number of problems can arise in the internal business environment, which can be prevented by building an internal control system.

The presented conclusions, which are based on the performed analysis, can be generalized for companies of other industries, and therefore the selected sample of companies is not a limiting factor. For this reason, we do not consider the selected sample as a limiting factor for the application of the obtained results. The procedure presented in the thesis can be used in any company where an internal control system is applicable.

The applicability of the results is not limited only to agricultural enterprises, as the issue of the internal control system affects enterprises in general.

Continuing the research in the field of internal control system, we would like to focus on defining the design, implementation and operting effectivness.

The content of the database is information from 46 respondents from the ranks of managers, financial directors and accountants and other employees responsible for the performance of control.

Therefore, in order to be able to analyze this influence, we had to quantify the range of responses to create a model. In the following Table 2 we present the estimated model containing endogenous and exogenous variables.

In the question "what type of personality best describes you in your work?", we chose the following range of answers:

- perceivers - they are realistic people who like to emphasize details. They use common sense and experience to solve the problem.
- thinkers – they tend to be preceded by a thorough analysis of the problem before their decisions. They weigh all the pros and cons, they are really honest and fair.
- judges – they like to be organized and prepared, they like to make plans and it is most convenient for them when they have different rules.

Label of the variable	Character. variable	Identification and monitoring of controls	A range of answers
PreferenceICS	Endogenous variable	Do you see a need to improve the internal control system?	0 - no 1 - yes
AccountSys	Exogenous variables	Do you think that the accounting system in your company is effective in terms of control processes?	0 - no 1 - yes
Automat		Do you think that the automation of internal control processes will make the performance of the control itself more efficient?	0 - no 1 - yes
Artificial variables: PersonTypesA PersonTypesB PersonTypesC		What type of personality best describes you in your work? (PersonTypeA – perceivers; PersonTypeB – thinkers; PersonTypeC – judges)	
Time		Are you willing to work overtime, if necessary?	0 - no 1 - yes
Self-development	Exogenous variable	Would you be interested in self-development in your work?	0 - no 1 - yes
Salary		Are you satisfied with the amount of your financial evaluation?	0 - no 1 - yes
Gender		Determine your gender.	0 - woman 1-man
Age		Which of the mentioned age categories do you belong to: 1. category - 30-49 years 2. category - 50 and more years	0 - 1. cat. 1 - 2. cat.
Children		Do you have children?	0 - has no child 1 - at least one child
Education		What is your highest level of education?	1 - secondary 2 - university

Source: Own processing based on data from a questionnaire survey.

Table 2: Estimated model with characteristics of endogenous and exogenous variables.

90% of women from the total number of women and 84% of men from the total number of men responded positively to the preference for improving the VKS. 28% of women out of the total number of women and 32% of men out of the total number of men responded positively to the question whether the respondents think that the company's accounting system is effective in terms of control processes. 71% of women out of the total number of women and 76% of men out of the total number of men responded positively to the question of whether the automation of internal control processes will make the performance of the control itself more efficient. In the case of overtime, 33% of women from the total number of women and 32% of men from the total number of men answered positively. 48% of women from the total number of women and 44% of men from the total number of men responded positively to the question about willingness to self-development. When asked about salary, we noted that 33% of women from the total number of women are not satisfied with their financial evaluation, while men were dissatisfied with 36% of the total number of men.

After specifying the variables we selected, we proceeded to select a specific type of model that would be suitable for the empirical analysis of the investigated issue. The basic assessment of model quality using Gretl statistical software is shown in the following Table 3.

Correctly predicted cases	46 (99.9%)
The maximum likelihood model method-Chi-square (p-value)	89.1433 (0.0000)

Source: Own processing based on data obtained from a questionnaire survey in selected accounting entities.

Table 3: Basic assessment of model quality.

The first statistic in Table 3 speaks about the significant predictive ability of the models, i.e. the model correctly predicted 99.9% of the values. Significance of the model based on a p-value that is less than our chosen significance level of 0.05, we can say that the model as a whole is highly significant. We consider the statistics of correctly predicted cases to be the most important statistic, and we say that the model is good because the model correctly predicts the values.

The following Table 4 shows the parameter estimates in the model that we estimated using Gretl statistical software. It is an analysis of individual preferences affecting the willingness to improve the internal control system.

Label of the variable	p-value	from logarithmic coef.	significance
AccountSys	0.9991	1.7846	
Automat	<0.0001	1.9973	***
PersonTypesA	0.6971	2.4407	
PersonTypesB	<0.0001	1.2246	***
PersonTypesC	0.9968	2.0872	
Time	0.9994	0.9780	
Self-development	<0.0001	1.7455	***
Salary	<0.0001	1.2435	***
Gender	<0.0001	1.7685	***
Age	0.9991	0.5006	
Children	0.9967	1.4533	
Education	0.9982	0.9892	

Source: Own processing based on data obtained from a questionnaire survey in selected accounting entities.

Table 4: Estimation of model parameters.

The exogenous variable in the logit model is the logarithmic ratio of the probabilities that the phenomenon will occur or will not occur. After this adjustment, the coefficients are interpretable. In the next chapter, we deal with the interpretation of the results of the analysis.

This subsection is devoted to the interpretation of the results from the analysis of managers' preferences. The variables "Automat, PersonTypeB, Self-development, Salary" and "Gender" have significant coefficients, so we marked them with three stars. Other variables are considered insignificant and unsuitable for the interpretation of their coefficients.

The variable "AccountSys" came out insignificant, based on which we cannot interpret the effect on the endogenous variable. At the same time, we do not confirm the assumption that the respondents consider the company's accounting system to be effective in terms of control processes. Out of the total number of respondents, only 30% of respondents confirmed that they consider the company's accounting system effective in terms of control processes.

With the variable "Automat", we assume that if the respondents agree that the accounting system in the selected accounting entity is effective in terms of control processes, it increases the willingness to improve the internal control system by 99.7%. This means that if the respondents are convinced that they have the automation of processes in the accounting system, which leads to a positive effect on the willingness to improve internal control. We see here a space for solving the issue of IT solutions for setting up automation control processes in the accounting system of the selected accounting entity itself. In our opinion, the more automated the process will be, e.g. in accounting, the less error will occur, e.g. in the accounting system itself and in its data processing. We hereby confirm our assumption, where we found that approximately 73% of respondents think that the automation of internal control processes will make the performance of selected internal controls more efficient.

Based on the results of the "PersonTypeB" variable, we can state that respondents who consider themselves to be thinkers have a higher willingness to improve the internal control system than other personality types by 22%. Thinkers were considered to be those who tend to have a thorough analysis of the problem before their decisions. They weigh every pros and cons, they are really honest and fair. These are employees who quickly adapt to new or changing risks or operational deficiencies, which has a positive effect on the improvement of the internal control system in the selected accounting entity.

In the case of the "Self-development" variable, we can state that respondents who are interested in training and want to realize themselves in self-development have a higher preference for improving the internal control system by 74%.

The variable "Salary" expresses a positive tendency to increase the willingness to improve the internal control system. Thus, respondents who are satisfied with their financial evaluation have an increased willingness to improve the internal control system by 24%.

As a result of the analysis of the "Gender" variable, we can assume that women have a higher willingness to improve the internal control system by 77%. This is an interesting finding, but at the same time it is confirmed to us during the personal meetings themselves, from which the same result was noticeable. Thus, women were more active also with regard to proposed changes to the implementation of the internal control system.

In our work, we achieved interesting knowledge and solutions, which were directly presented to the management of selected accounting entities. At the same time, it should be emphasized that the knowledge gained from our study is also suitable for publishing scientific articles.

Conclusion

In the article, we focused on the analysis of preferences for improving the internal control system in selected accounting entities. On the basis of which we achieved interesting findings from the point of view of management and executives in selected accounting entities. As a result, these exogenous variables "Automat, PersonTypeB, Self-development, Salary" and "Gender" were suitable for interpretation due to the fact that they have significant "p-value" coefficients. Other exogenous variables are considered insignificant and unsuitable for interpreting their coefficients.

With our findings from the analysis of managers' preferences, we can state that the decisive factors that contribute to the willingness to improve the internal control system are the automation of control processes. Another finding is that managers who make a decision based on a thorough analysis of the problem contribute to the willingness to improve the internal control system. Managers' satisfaction with financial evaluation was also a decisive factor, and therefore those employees who were satisfied with their financial evaluation were also more willing to improve the internal control system.

With the variable "Automatic" we can assume that if the respondents who agreed that the accounting system in the selected accounting entity is effective in terms of control processes, they are more willing to improve the internal control system by 99.7%. We see here a space for solving the issue of IT solutions for setting up automation processes of control in the accounting system of the selected accounting entity itself. As we already mentioned during the actual testing of internal controls, the more automated the process will be, e.g. in accounting, the less error will occur, e.g. in the accounting system itself and in its data processing. At the same time, we also confirm our assumption, where we found that approximately 73% of respondents think that the automation of internal control processes will make the performance of selected internal controls more efficient. With the exogenous variable "PersonTypeB", we can state that respondents who consider themselves thinkers have a higher willingness to improve the internal control system than other types. Their preference for improving the internal control system is higher by 22%.

Thinkers were considered to be those who tend to have a thorough analysis of the problem before their decisions. They weigh all the pros and cons, they are really honest and fair. They quickly adapt to new or changing risks or operational deficiencies, which has a positive effect on the improvement of the internal control system in the selected accounting entity. Based on the results of the exogenous variable "Self-development", we can state that respondents who are interested in training and want to realize themselves in self-development have a higher preference for improving the internal control system by 74%. We also noticed a positive trend in the "Salary" variable, which contributes to an increase in the willingness to improve the internal control system. On the basis of which we can claim that respondents who are satisfied with their financial evaluation have an increased willingness to improve the internal control system by 24%.

In conclusion, we found an interesting result of our analysis for the variable "Gender", where our assumption is that women have a higher willingness to improve the internal control system by 77%. We consider this to be an interesting finding, but at the same time it is also confirmed by the personal meetings themselves, from which the same result was noticeable. Thus, women were also more active regarding the proposed changes to the implementation of the internal control system.

The internal control system should be designed, implemented and maintained by those charged with governance, managers and other employees to provide reasonable assurance about the achievement of the entity's objectives, in cases of reliability of financial reporting, efficiency of operations and compliance with applicable laws and regulations.

From the obtained results, we suggest to accounting entities the automation of the internal control process in the accounting system, which would have a positive effect on a smaller amount of errors in the control process itself. Managers should be interested in trainings and should want to realize themselves in self-development, which will also contribute to less erroneous entries. Managers should especially have a thorough analysis of the problem before their decisions. They should be able to quickly adapt to new or changing risks or operational deficiencies, which also has a positive effect on improvement of the internal control system. An important aspect is also the financial motivation of managers, which would contribute to the improvement of the internal control system.

In the article, we achieved interesting knowledge and solutions designed to contribute to the improvement of the internal control system in selected accounting entities. At the same time, it is necessary to emphasize that the knowledge gained from our studies are also suitable for publishing scientific articles. This approach to the analysis of testing the internal control system through a questionnaire survey of managers can be applied in various business entities, which is how we brought added value not only in accounting entities focusing on agriculture.

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Agris on-line Papers in Economics and Informatics

Volume XVII Number 1, 2025

Food Insecurity in Asia Pacific: Climate Change and Macroeconomic Dynamic

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Abstract

This study analyzes the effect of climate change and macroeconomic factors on food security in Asian Countries with moderate to weak food security ratings. This study finds significant findings using panel data from 14 countries in the Asia Pacific Region from 2012 to 2021. First, climate change variables measured by CO_2 carbon emissions significantly negatively impact food security. Increased carbon emissions can threaten crop production, alter rainfall patterns, and increase vulnerability to natural disasters. Second, macroeconomic variables such as agricultural value added, food price inflation, exports, and GDP per capita also show significant adverse effects. Global crises such as the COVID-19 pandemic, geopolitical conflicts, and U.S. monetary policy have impacted food prices, agricultural production, and per capita income, disrupting supply chains and increasing food security risks. However, the positive findings related to food imports and the Per Capita Production Index suggest that food imports can improve supply diversification, food availability, and food price stability, which are essential strategies for strengthening food security in the Asian Region. This research highlights the importance of carbon emission mitigation, macroeconomic crisis management, increased local food production, and import policies in facing the complex challenges of food security amidst climate change and global economic dynamics.

Keywords

Food insecurity, climate change, agricultural value added, food price inflation, gross production index per capita, agricultural net export.

Marwa, T., Hamira, Sukanto, Mukhlis, Atiyatna, D. P. and Hamidi, I. (2025) "Food Insecurity in Asia Pacific: Climate Change and Macroeconomic Dynamic", *AGRIS on-line Papers in Economics and Informatics*, Vol. 17, No. 1, pp. 81-94. ISSN 1804-1930. DOI 10.7160/aol.2025.170107.

Introduction

Food security significantly impacts poverty reduction and is critical to social and economic development. Food security improves health and productivity by ensuring access to sufficient, safe, and nutritious food, helping families escape poverty. In developing countries, many poor people depend on agriculture, benefiting from the increased productivity catalyzed by food security, which directly increases their incomes. Food price stability, an essential component of food security, is significant for poor families who allocate a large proportion of their income to food, allowing them to plan their spending better and avoid food crises. Food security also enables investment in education, which is critical for future generations to fight poverty. In addition, food security increases resilience to economic crises and natural disasters, enabling poor families to survive in difficult conditions. Food security is essential in building national resilience and a fundamental cornerstone of economic development. Secure food production contributes to economic development by reducing poverty and inequality. Food security contributes to agriculture, tourism, and food processing, which is essential in attracting investment and economic growth (Naidanova and Polyanskaya, 2017).

By 2022, an estimated 51 million people are in crisis in Asia's five largest food-insecure countries. This is a significant increase from around 29 million in 2021. This increase is mainly due to the addition of Myanmar and Sri Lanka as countries experiencing major food crises (Food Security Information Network Required citation FSIN & Global Network Against Food Crises, 2023), accounting for more than 21 million people in acute food insecurity in 2022. Afghanistan faces the worst food crisis in Asia, with 39 percent of its regional population experiencing acute food insecurity, followed by Myanmar, Pakistan, Sri Lanka, and the Cox's

Bazar region of Bangladesh. The impact of the food crisis is inseparable from various variables, such as the primary trend of the subject of food crisis, namely global warming and climate change. (Lee, Wang, and Thinh, 2023; Lee, Zeng, and Luo, 2024; Yang and Hamori 2023). Especially in terms of extreme weather (de Amorim et al., 2018; Ledda et al. 2020, 2021) significantly affecting food production, including aspects of quality, price, and supply chain (de Amorim et al. 2018; Jin et al. 2023; Lee, Zeng and Luo, 2024). A broader focus on Food Security in research emphasizes the increase in global food crises and severe food insecurity in 2022, triggered by economic shocks, geopolitical situations, climate change, and extreme weather events. (Amiraslani and Dragovich, 2023; Ceballos, Hernandez and Paz, 2021; Chriest and Niles, 2018; Naidanova and Polyanskaya, 2017; Rice, Einbinder and Calderón, 2023).

Extreme weather (Aragie et al., 2023; Gebre and Rahut, 2021; Hadebe, Modi and Mabhaudhi, 2017) global supply chain risks such as the COVID-19 pandemic (Devereux, Béné and Hoddinott, 2020; Dietrich et al., 2022; Gerard, Imbert and Orkin, 2020; Sassi and Trital, 2023) and the war in Ukraine (Abay et al., 2023; Bechdol et al., 2022; Glauber and Laborde Debucquet, 2023; Mottaleb, Kruseman and Snapp 2022), as well as the energy crisis in recent years (Byerlee, Falcon and Naylor, 2017; Naylor and Higgins, 2018) rising and volatile agricultural and food prices (Amolegbe et al., 2021; Oluwaseyi, 2018; Shittu et al., 2017), has triggered instability in the agricultural sector. Triggering instability in the agricultural sector and increasing the risk of insecurity, as reported by the Food and Agriculture Organization (2023) and the World Trade Organization (2023), as well as country-level policies, continue to promote agricultural exports to stimulate economic growth in poor countries. However, market failure, infrastructure, investment, and supply chain issues are the main problems in food security issues in developing countries. A study conducted by Rudolf (2019) and Mgomezulu et al. (2023) shows that these investments contribute to poverty alleviation and improved food security.

This is achieved through increased agricultural production and sales, as found by the studies of Mutegi et al. (2024) and Samdrup et al. (2023). Such investments are also associated with increased demand for more diverse and nutritious food, as Sultana and Sadekin (2023) found. However, the influence of increased agricultural production as a significant factor of supply chain development on dietary diversity and food security among rural populations, especially in the Small Island Developing States (SIDS) region, has not been recognized (Santangelo, 2018; Songsermsawas et al., 2023; Syddall, Fisher and Thrush, 2022). Agricultural export policies lead to an increase in consumption and drive food security instability, the findings of several studies show the adverse effects of export policies on food security conditions in Low-Income Countries. The concerns of several researchers found that there is a potential neglect of small subsistence farms, which could result in a slowdown in productivity growth. At the same time, the dynamics of market integration support agricultural exports but there are trade-off effects between domestic food production and domestic markets (Campi, Dueñas and Fagiolo, 2020, 2021).

Agricultural policies significantly increase agricultural production and impact climate change risks. The trade-off between policies in increasing production capacity, such as increasing agricultural production land, agricultural technology, and farmer productivity (Lee, Wang and Thinh, 2023; Lee, Zeng and Luo, 2024; Yang and Hamori, 2023). Several studies have found that the impacts of increasing agricultural production, including greenhouse gas emissions, are often associated with increased fertilizer use, which can result in greenhouse gas emissions that impact climate change. Land use and expansion of agricultural land often means deforestation or other land conversion, which reduces CO_2 sequestration by vegetation, land use, deforestation, and carbon sequestration can show their impact on climate change.

According to Economist Impact (2022), the four main pillars of food security are availability, accessibility, utilization, and stability of the food system. Several studies have examined the relationship between climate change and food security. Some studies found an inverse relationship between climate change and food security, climate change can reduce food availability, especially in Sub-Saharan and South Asian regions where many nutritional problems occur (Affoh et al., 2022; Fuller et al., 2018; Stuch, Alcamo and Schaldach, 2021). Studies analyzed the impact of temperature variations on maize, wheat, and soybean production. The results showed that rising global temperatures adversely affect crop yields, leading to food shortages. Another study revealed that climate change reduces aquatic food production and crop productivity in Asia and Africa (Affoh et al., 2022; Chandio et al., 2023, 2022; Zhao et al., 2017).

Climate change negatively affects food availability, especially in Sub-Saharan Africa and South Asia. Climate change generally disrupts food production in Asia, but its impacts vary across regions. Several studies in the Asian region show the impact of climate change on food crop production in the South (Fahmida, Chaudhary, and Hanif 2022; Yan and Alvi 2022) with the findings that temperature and carbon emissions adversely affect long-term food crop production, while rainfall supports long-term food crop production in the region, climate change decreases cereal production, increases cereal prices, and decreases domestic consumption and income. The study further states that rising temperatures and carbon emissions significantly reduce long-term rice production in Asia. On the other hand, rainfall increases rice production in the Asian region in the long run. (Mumuni and Joseph Aleer 2023; Trnka et al. 2019).

Food security does not only depend on agricultural production, but several studies found that macroeconomic variables such as population, per capita income, poverty, exports, and imports have a significant effect on food security (Ceballos, Hernandez, and Paz 2021; Chriest and Niles 2018; Naidanova and Polyanskaya 2017; Rice, Einbinder, and Calderón 2023). In addition, findings from several studies show that population growth has a significant negative impact on food security in the short term and an insignificant negative impact on food security in the long term (Bakari, Mabrouki and Elmakki, 2018; Ceesay and Ndiaye, 2022; Sun and Zhang, 2021). Other macroeconomic indicators related to GDP per capita have varying findings; some studies found that an increase in GDP per capita positively impacts food security, while other studies show that economic growth in the agricultural sector determines food security in Asian and African countries. Other studies show that economic growth does not significantly affect food security in Low-Income Countries (Gnangnon, 2023; Sassi and Trital, 2023).

Materials and methods

This study uses climate change variables (CO_2 Carbon Emissions) and macroeconomic variables, namely (agricultural value added, food Price Inflation, Gross Production Index per capita, Agricultural Export and Import) to model the effect of climate change and macroeconomic variables on food security in Asian countries that have food security ratings categorized as having moderate and weak scores in the world food security index (Economist Impact, 2022). The panel data linear regression model analyzes the impact of climate change and macroeconomic variables on food security in 14 Asia Pacific countries from 2012 to 2021. The countries selected were Indonesia, Thailand, Azerbaijan, Philippines, India, Myanmar, Uzbekistan, Nepal, Tajikistan, Cambodia, Sri Lanka, Bangladesh, Laos, and Pakistan (Economist Impact, 2022). This method is thoroughly analyzed by considering variations between time and between countries. The econometric model specifications are as follows:

$$FS = f(CO2, VA, FPI, GPcap, EX, IMP)$$

Equation (1) is expressed in explicit and econometric form as follows:

$$FS_{it} = \beta_0 + \beta_1 CO2_{it} + \beta_2 VA_{it} + \beta_3 FPI_{it} + \beta_4 GPCap_{it} + + \beta_5 EX_{it} + \beta_6 IMP_{it} + \beta_7 GDPCap_{it} \varepsilon_{it}$$

Where *FS* = Food Security Index, β_0 = Constant, β_1- β_7 = Regression coefficient, *VA* = Added Value of Agriculture Sector, *FPI* = Food price inflation, *GPcap* = Per capita production index, *EX* = export, *IM* = Import and *GDPcap* = GDP per capita growth rate ε_{it} = error of term, *i* = 14 Asia Pacific countries, *t* = 2012-2021 period.

This model was estimated by comparing three approaches, namely the Common Effect Model (CEM), Fixed Effect Model (FEM), and Random Effect Model (REM). CEM assumes no differences between countries, with the same intercept for each country and time. FEM takes into account fixed differences between countries, with a different intercept for each country. REM assumes that differences between countries are random and uncorrelated with independent variables. To select the best model, the Chow test was carried out to compare CEM with FEM, the Hausman test to determine whether FEM or REM was more suitable, and the Lagrange Multiplier (LM) test to evaluate whether REM was better than CEM. If the test results show that differences between countries are fixed and significant, the FEM would be a better choice. On the other hand, if differences between countries are considered random and not correlated with independent variables, then the REM is more appropriate (Greene, 2012).

Several models were considered in the initial stages, including Pooled Mean Group (PMG) and Autoregressive Distributed Lag (ARDL), considering the potential for variables with mixed integration between I(0) and I(1). However, after testing stationarity using the Levin, Lin, and Chu (LLC), Im, Pesaran, and Shin (IPS), and Augmented Dickey-Fuller (ADF) methods, the results showed that all variables were stationary at level [I(0)]. Thus, this study does not apply the ARDL and PMG models, which are generally used for variables with mixed levels of integration. Instead, this research uses three main panel data regression models: the Common Effect Model, Fixed Effect Model, and Random Effect Model. To select the best model among the three models, Chow, Hausman, and Lagrange Multiplier tests were carried out. These models were chosen because they better fit the stationarity of the existing data, thus allowing the analysis of linear relationships between variables without considering long-term cointegration.

The panel data regression approach is very appropriate to apply in this research because panel data allows a more in-depth analysis by combining dimensions across time (time-series) and across units (cross-sectional) so that it can accommodate heterogeneity between units that cannot be observed through classical linear regression (Baltagi, 2005; Wooldridge, 2010). The CEM assumes no heterogeneity between units, so each unit is treated equally. The FEM, on the other hand, considers individual variation between units by including a specific intercept for each unit, so this model is used when specific differences between units can influence the dependent variable (Hsiao, 2003). The REM assumes that differences between units are random and uncorrelated with independent variables, making it more efficient if this assumption is valid (Baltagi, 2005; Greene, 2012).

To select the best model, statistical tests such as the Chow Test are used to compare CEM and FEM, the Hausman Test to differentiate between FEM and REM, and the Lagrange Multiplier Test to compare CEM and REM. Selecting the suitable model ensures that the model used accurately reflects the characteristics of the data. The use of panel data regression is based on its superiority in analyzing inter-unit heterogeneity and variable dynamics in the time dimension. Therefore, although the Compound Linear Regression Model (LRM) was considered, the panel nature of the data encouraged the use of the CEM, FEM, and REM models, which follow the econometric theory outlined by Baltagi, 2005; Wooldridge, 2010; Hsiao, 2003.

This study uses panel data from 14 countries in the Asia Pacific region, with the selection of countries based on the Global Food Security Index (GFSI) which calculates a country's food security score. This index assesses food security based on availability, accessibility, quality, and sustainability. The countries selected for analysis had a food security score ≥ 60, indicating the moderate to weak category according to the GFSI classification. In more detail, countries with a score of 60 to 69 are categorized as moderate, while countries below 60 are considered to have weak food security. The countries included in this study, such as Indonesia, Thailand, the Philippines, India, and Bangladesh, are in the moderate category. In contrast, countries such as Myanmar, Nepal, Laos, and Tajikistan tend to be in the weaker category. These countries face significant challenges related to food access and distribution, although they do not fall into the lowest category in terms of food security. The selection of countries with a score ≥ 60 focuses on countries that are in food security, which requires specific policies to increase food accessibility, improve distribution infrastructure, and increase resilience to climate change and economic crises.

Thus, climate change data (proxied by CO_2 carbon emissions from agricultural land use) in the Food and Agriculture Organization. While macroeconomic indicators (proxied by data on agricultural value added, food price inflation, per capita production index, Export and Import Index, and per capita GDP growth rate measured in percent) in the World Bank. Food security is measured using the World Food Security Index based on the four main pillars of food security: availability, accessibility, utilization, and stability of the food system (Economist Impact, 2022). Table 1 summarizes the variables described by symbol and measurement as follows:

Variables	Symbol	Measurement	Source	Scale
Food security	FS	Food Security is an index of global food security measured based on 4 pillars: availability, accessibility, utilization, and stability of the food system.	Economist Impact	Ratio
Carbon emissions	CO_2	Carbon Emissions is the percentage of carbon emissions resulting from agricultural production	Food and Agriculture Organization	Ratio
Value added in the agriculture sector	VA	Value Added is the distribution of agricultural production measured by the percentage of value added in the agricultural sector.	World Bank	Ratio
Food price inflation	FPI	Food price inflation is the rate of food price inflation as measured by percentage.	World Bank	Ratio
Per capita production index	GPCap	Agricultural Production is measured based on the index of agricultural production per capita	World Bank	Ratio
Export	EX	Agricultural sector exports are the total value of goods and services sold abroad, calculated using the ratio method to show the contribution of exports to the economy quantitatively	World Bank	Ratio
Import	IMP	Agricultural sector imports are the total value of goods and services purchased from abroad, measured accurately using a ratio scale to reflect the influence of imports on the agricultural sector economy.	World Bank	Ratio
GDP per capita growth rate	GDPCap	The GDP per capita growth rate is measured as the annual percentage change in GDP per capita, directly indicating the country's economic growth rate in the context of increasing output per capita.	World Bank	Ratio

Source: Own processing

Table 1: Definition and measurement of variables.

Results and discussion

The state of food security in the Asia Pacific region

Food security scores in the Asia Pacific region reflect challenges and successes that vary depending on the country and its context. Food security is measured based on several critical factors, including food availability, access to food, food utilization, and stability of food supply. Table 2 shows significant differences in food security among countries in the Asia Pacific region. The highest ranking of countries with a scoring category of "Good", countries such as Japan, New Zealand, Australia, China, Singapore, Kazakhstan, and South Korea show strong food security. Japan, with a score of 79.5, showed remarkable stability with no change from the previous year. New Zealand and Australia, with scores of 77.8 and 75.4, respectively, recorded improvements, especially in Australia, with a significant increase of 4.7 points. China and Singapore also increased their rankings. In the "Moderate" category, countries such as Malaysia, Vietnam, Indonesia, Thailand, Malaysia, and Vietnam. On the other hand, Indonesia and Thailand showed stable scores but signaled the need to continue improving food access and quality. India also recorded an improvement in its ranking.

Country	GOOD (Score 70-79.9)	Δ
Japan	79.5	0
New Zealand	77.8	0.4
Australia	75.4	4.7
China	74.2	3.6
Singapore	73.1	0.3
Kazakhstan	72.1	1.4
South Korea	70.2	1.3
MODERATE (SCORE 55-69.9)		
Malaysia	69.9	-1.6
Vietnam	67.9	+5.2
Indonesia	60.2	+0.4
Thailand	60.1	-2.0
Azerbaijan	59.8	-1.0
Philippines	59.3	-0.3
India	58.9	+0.5
Myanmar	57.6	-0.7
Uzbekistan	57.5	+3.0
Nepal	56.9	+1.8
Tajikistan	56.7	+2.3
Cambodia	55.7	+0.7
Sri Lanka	55.2	-0.3
WEAK (Score 40- 54.9)		
Bangladesh	54.0	+0.4
Laos	53.1	+4.1
Pakistan	52.2	+2.2

Source: Economist Impact, 2022

Table 2: scoring of food security in the Asia Pacific region.

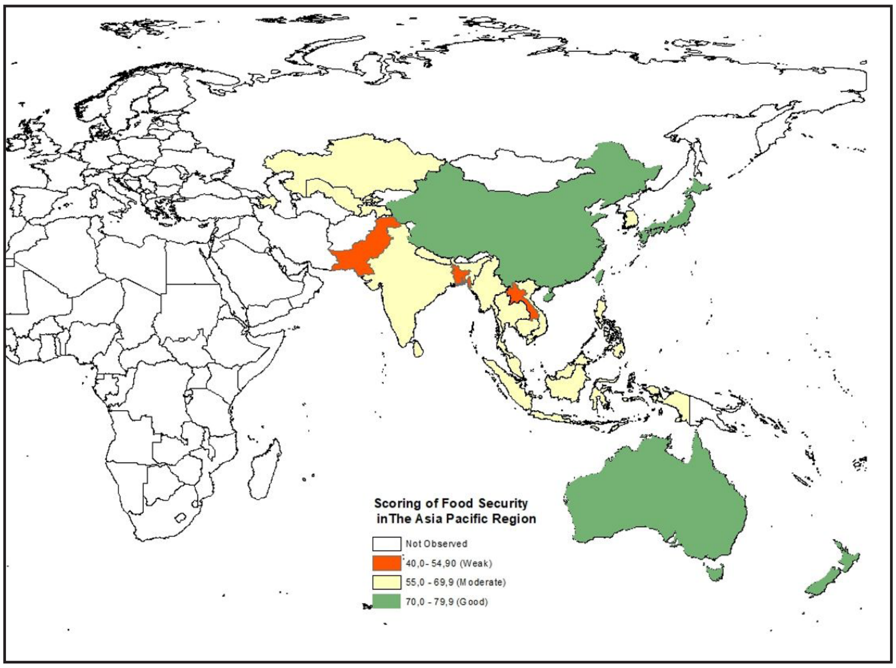
Changes in food security scores (Δ) in Asia Pacific show significant shifts in various countries. Australia recorded the largest increase with a 4.7 point increase, followed by Vietnam with a 5.2 point increase and Laos with a 4.1 point increase. Uzbekistan also experienced a significant increase of 3.0 points, while China increased 3.6. Several other countries, such as Kazakhstan and South Korea, showed moderate increases of 1.4 and 1.3 points, respectively. On the other hand, Malaysia experienced the most significant decline, with a decline of 1.6 points, followed by Thailand, which fell 2.0 points, and Azerbaijan, with a decline of 1.0 points. Slight declines also occurred in Myanmar and the Philippines, with 0.7 and 0.3 points respectively.

Although some countries are showing improvements in food security, others are still facing declines. Countries with "Weak" scores, such as Bangladesh (54.0), Laos (53.1), and Pakistan (52.2), face severe challenges in food security. Although Laos recorded an increase of 4.1 points and Pakistan rose 2.2 points, they remained below a score of 60, indicating a state of low food security and the need for further action to improve food access and stability. Food security scores are measured based on the Food Security Index, with a good score category symbolized by green, a moderate score category categorized by light gold, and a weak score category symbolized by orange (see Figure 1).

Econometric analysis

The test begins with stationarity testing of LLC, IPS, and ADF. The results of the Root Test show that Food Security, Carbon Emissions, Agricultural Value Added, Food Price inflation, Per capita Production Index, and Export are stationary at their level, so they are integrated at order zero [i.e., i.e./I(0)]. However, GDP per capita is not stationary at the first level, indicating that imports and GDP per capita growth rate are integrated in order one [i.e. I/(1)]. However, based on IPS and ADF tests show that all variables are stationary at the level integrated at zero order [i.e., i.e.,/I(0)] see Table 3, so based on these results, linear regression testing is carried out without applying ARDL.

After testing to determine the appropriate model between Multiple Linear Regression or Pooled Mean Group (PMG) and Autoregressive Distributed Lag (ARDL), the results in Table 1 show that ARDL cannot be used because all variables are stationary at the first level of difference (first difference) and integrated at zero order [I(0)]. The ARDL model is designed to estimate long-term relationships in data with a mixture of integration between I(0) and I(1), so it is inappropriate if all variables are stationary at the same level. Therefore, ARDL is unsuitable because it cannot accommodate long-term relationships with the variable I(0). In contrast, PMG and Multiple Linear Regression



Source: Data Economist Impact (2022), processed by the author

Figure 1: Map of food security classification in Asia Pacific.

Variables	Levin, Lin and Chu (LLC)	Im-Pesaran Shin (Social Studies)	Augmented Dickey-Fuller ADF)
FS	-2.89683***	-3.6687***	-4.53709***
CO_2	-7.3061***	-4.3995***	-4.24821***
FPI	-2.87622***	-3.28848***	-4.2477***
GpCap	-5.30612***	-3.23627***	-4.13324***
EX	-1.88558**	-3.02443***	-3.68188***
IM	0.3022	-1.96888**	-3.0649***
GDPcap	5.31898	-2.87735***	-2.47953**

Note: ****, **, and * indicate significance levels of 1%, 5%, and 10%, respectively
Source: Processed by the authors

Table 3: Panel Unit Root Test results.

models are considered because they are more suitable for panel data with stationary variables at the same level. PMG allows analysis that considers interunit heterogeneity in long-term and short-term dynamics. In contrast, Multiple Linear Regression focuses on estimating linear relationships without considering cointegration, making it more appropriate to use in this study. Testing was carried out by comparing three-panel data regression models, namely the CEM, FEM, and REM, using statistical tests such as the Chow Test, Hausman Test, and Lagrange Multiplier Test to determine the most appropriate model (see Table 3).

Although PMG and ARDL models were initially considered in the methodology, these models were not implemented because all variables were proven to be stationary at the [I(0)] level, so CEM, FEM, and REM were preferred adequately applied. ARDL and PMG are more appropriate to use when there are variables with a mixed level of integration between I(0) and I(1), which was not found in this study. The Common Effect Model estimation results show that the variables VA (Value Added), GPCAP (Gross Production Per Capita), EX (Exports), and GDPCAP (GDP per Capita) are statistically significant at the conventional significance level (p-value close to 0), indicating that These variables have a significant influence on the dependent variable, namely food safety. On the other hand, the CO_2 and IM (Import) variables are not statistically significant because they have a probability value greater than the significance level used. Adjusted R^2 of 0.659 indicates that this model can explain around 65.9% of the variation in the dependent variable.

Comparison of panel data regression results are analyzed in detail, namely (1) The results of the CEM: variables VA, GPCAP, EX, and GDPCAP show high levels of statistical significance (probability values close to 0,0000). This indicates that these variables strongly and significantly influence the food security variable. CO_2 and IM are not statistically significant in this model, characterized by probability values more incredible than the significance level. The Adj R_2 in the CEM shows a value of 0.659 indicating that this model can explain about 65.9% of the variation in the dependent variable, which is quite good but not optimal. (2) The results of the FEM show that the variables CO_2, VA, GPCAP, EX, IM, and GDPCAP show a high level of statistical significance (probability value close to 0,0000), while the FPI variable shows an insignificant effect with a probability greater than α. With a value of 0.8712, this model shows a better explanation (87.12%) of the variation in the dependent variable compared to the CEM, indicating that this model is more optimal in explaining the data. (3) The results of the REM test show that the variables VA, FPI, GPCAP, and GDPCAP are statistically significant with an ADJ R-value of 0.4505 lower than the FEM, indicating a lower explanation of the variability in explaining the food security variable. Based on the Chow Test results with a Prob value of 0.000 indicates a significant difference between the CEM and other models, so the FEM is more suitable. Based on the Hausman Test shows a Prob value of 1,000, which explains why the REM is more suitable. There is a difference in the test results so the last test is the LM test with the Breusch Pagan Test results, therefore the model chosen is the REM. The best selection in the panel data regression model is based on three tests: Chow, Hausman, and LM. However, statistical reviews such as the significance level of the t-statistic, F-statistic, and coefficient of determination are needed to determine the model's implications (Gujarati, 2004; Greene, 2012). Based on most variables' high adjusted R-squared value and statistical significance, the fixed effect model is the most suitable for theoretical implications.

Variables	Common Effect Model		Fixed Effect Model		Random Effect Model		Best Model Selection		
	Coefficient	Prob	Coefficient	Prob	Coefficient	Prob	Chow Test	Hausman Test	Breusch Pagan Test
CO_2	0.002109	0.7383	-0.064501	0.0138**	-0.01131	0.5008	0.000***	1	0.000***
VA	-0.239144	0.000***	-0.708028	0.000***	-0.47633	0.000***			
FPI	-0.070479	0.1101	-0.061181	0.223	-0.10467	0.001***			
GPCAP	0.100555	0.000***	0.07211	0.0007***	0.078341	0.021**			
EX	0.782864	0.000***	-2.726399	0.000***	-0.50586	0.2991			
IM	0.082492	0.7324	3.58967	0.0011***	1.517663	0.0345**			
GDPCAP	-0.220819	0.0008***	-0.132829	0.0031***	-0.16103	0.01480**			
C	37.308	0.000***	48.06736	0.0049****	41.0669	0.000**			
AdJ R^2	0.659		0.8712		0.4505				
Prob-F	0.000***		0.0000***		0.00000***				

Note: ****, **, and * indicate significance levels of 1%, 5%, and 10%, respectively
Source: Processed by the authors

Table 4: Model comparison results and best model selection.

Discussions

The results of the model selection show that the Fixed Effect Model was chosen as the model analyzed for the empirical discussion of the influence of climate change and macroeconomics on food security in the Asia Pacific Region. The results show that the climate change variable proxied by carbon emissions significantly negatively influences food security. In line with several findings, increasing CO_2 emissions and their impact on climate change have the potential to significantly impact food security in the Asian region. Rising global temperatures can threaten crop production, change rainfall patterns, and increase vulnerability to natural disasters that can potentially reduce food supplies. From the perspective of macroeconomic theory, this can be explained through the negative externality mechanism caused by carbon emissions, where an increase in carbon emissions functions as a negative supply shock which directly reduces the productivity of the agricultural sector. The Solow-Swan model with externalities demonstrates how climate change reduces total factor productivity (TFP), resulting in a decline in agricultural output and threats to food security. Another approach, namely the DSGE (Dynamic Stochastic General Equilibrium) model, integrates climate change into real sector equations and shows that climate change causes significant food disruptions in production through a decrease in the quality of production factors such as land and air, which directly reduces supply (de Amorim et al., 2018; Ledda et al., 2020, 2021; Lee, Zeng, and Luo, 2024; Lee, Wang and Thinh, 2023; Yang and Hamori, 2023).

Meanwhile, based on macroeconomic indicators, the variables of value added in the agricultural sector, food price inflation, exports, and GDP per capita statistically show a negative and significant influence on food security. This explanation aligns with the Phillips Curve theory, which states a negative relationship between inflation and unemployment. In this context, rising food price inflation, especially in developing countries, causes an increase in the cost of living which suppresses people's purchasing power and reduces aggregate demand, which in turn slows down economic growth. High inflation creates more significant economic uncertainty, reduces market confidence, and ultimately affects economic stability, directly impacting the food sector and food security.

The open IS-LM model explains how US interest rate policy, especially in the context of Quantitative Tightening (QT), causes capital outflows from Asian countries, which weakens their exchange rates. Exchange rate depreciation increases the cost of importing food and agricultural inputs, which ultimately reduces GDP per capita and reduces added value in the agricultural sector. This condition is explained by the health crisis conditions, namely COVID-19 19, the Ukraine-Russia war, and the Quantitative Tightening (QT) policy of the US central bank due to soaring inflation rates in the United States by increasing interest rates which led to weakening exchange rates in the Asian region which caused supply chains to be hampered, especially in food production. This crisis could not be contained by most countries in the Asian Region, especially Income Countries, so there was a surge in food prices which resulted in a decrease in the added value of the agricultural sector which reduced domestic food production and decreased GDP per capita. As described in several studies related to global supply chain risks such as the COVID-19 pandemic (Devereux, Béné and Hoddinott, 2020; Dietrich et al., 2022; Gerard, Imbert and Orkin, 2020; Sassi and Trital, 2023) and the war in Ukraine (Abay et al., 2023; Bechdol et al., 2022; Glauber and Laborde Debucquet, 2023; Mottaleb, Kruseman and Snapp, 2022), as well as the energy crisis in recent years (Byerlee, Falcon and Naylor, 2017; Naylor and Higgins, 2018) rising and volatile agricultural and food prices (Amolegbe et al., 2021; Oluwaseyi, 2018; Shittu et al., 2017), has triggered instability in the agricultural sector.

Triggering instability in the agricultural sector and increasing the risk of food crises. Hindered supply chains also lead to increased agricultural exports to meet the needs of other countries, resulting in trade-off effects that drive food security instability, the findings of several studies show the negative effects of export policies on food security conditions in Low-Income Countries findings show the potential neglect of small subsistence agriculture, which can result in slowing productivity growth, market integration supports agricultural exports, but there are trade-off effects between domestic food production and domestic foreign markets (Campi, Dueñas, and Fagiolo 2020, 2021). Food imports and per capita production index statistically positively influence food security in Asian countries by increasing supply diversification, sufficient food availability, and maintaining food price stability. When local production is insufficient to meet the community's food needs to encourage production balance and increase production, import policies are needed to encourage the per capita production index in the Asian region. This is in line with the findings of the increasing influence of agricultural production and imports as a significant factor of supply chain development on food diversity and food security among rural populations, especially in the Small Island Developing States (SIDS) region (Santangelo, 2018; Songsermsawas et al., 2023; Syddall, Fisher and Thrush, 2022).

Conclusion

The results of this study reveal some significant findings regarding the influence of climate change and macroeconomics on food security in the Asia Pacific Region. Climate change variables measured by carbon emissions significantly negatively impact food security. Increased carbon dioxide (CO2) emissions and climate change impacts can threaten crop production, change rainfall patterns, and increase vulnerability to natural disasters. Furthermore, macroeconomic aspects also have a significant influence on food security. Variables such as agricultural value added, food price inflation, exports, and GDP per capita show a significant negative influence. Global crises such as the COVID-19 pandemic conflicts such as the war in Ukraine, and monetary policies such as Quantitative Tightening (QT) in the United States impact food prices, agricultural production, and income per capita. This disrupts supply chains and increases food security risks. Empirical studies show that when the exchange rate weakens, countries that depend on food imports experience sharp increases in domestic food prices. This is because depreciation increases imported food prices, exacerbating price instability and threatening food security (Reboredo and Ugando, 2014). Thus, the QT policy in the US indirectly affects food prices in the Asian region through exchange rate transmission and increases in import costs.

Positive findings related to food imports and per capita production index. Food imports positively influence food security by increasing supply diversification, sufficient food availability, and maintaining food price stability. The research underscores the importance of reducing carbon emissions to address the impacts of climate change on food security and the importance of policies to improve food security in the face of macroeconomic crises. Increased local food production and optimized import policies are needed to ensure regional food security. Regional cooperation can also strengthen efforts to address food security issues amid the complexities of climate change and global economic dynamics.

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Agris on-line Papers in Economics and Informatics

Volume XVII Number 1, 2025

An Ontology-Driven Framework for Animal Traceability in Botswana

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Abstract

This study developed an ontology-driven framework for animal traceability (ODF-AT) in Botswana, aiming to enhance interoperability, integration, and standardization among stakeholders in the livestock sector. The framework addresses challenges in disease monitoring, theft prevention, and compliance with international trade standards. A mixed-methods approach was employed, utilizing qualitative and quantitative data collection through interviews, structured questionnaires, and project mapping with NVivo software. Stakeholders, including farmers, veterinary professionals, government officials, and Botswana Meat Commission representatives, provided insights into current practices and traceability challenges. The ODF-AT consists of four layers: input, semantic core, knowledge management, and application. It integrates technologies like ontology-based knowledge management and sensor devices, enabling real-time data capture, secure processing, and user-friendly interfaces. Results show that the ODF-AT improves data exchange and communication among stakeholders, offering a scalable and reliable system for livestock management. Although the framework shows promise, further research is needed to adapt it for other regions, overcome practical implementation challenges, and validate its effectiveness through pilot projects.

Keywords

Animal traceability, ontology-driven framework, interoperability, livestock management, food safety, disease control.

Mokgetse, T. L., Hlomani, H., Sigwele, T. and Zlotnikova, I. (2025) "An Ontology-Driven Framework for Animal Traceability in Botswana", *AGRIS on-line Papers in Economics and Informatics*, Vol. 17, No. 1, pp. 95-112. ISSN 1804-1930. DOI 10.7160/aol.2025.170108.

Introduction

Effective traceability systems are essential for ensuring food safety and quality, addressing growing consumer concerns about the authenticity and origin of animal products. The ability to trace the movement of animals and their related products is key to success in animal disease control (Salina et al., 2021). Effective traceability not only meets consumer demands for transparency and safety but also strengthens compliance with international trade regulations, opening up access to premium markets that value both animal welfare and traceability (Nkatekho, 2024). Technologies such as RFID, DNA fingerprinting, and chemical component fingerprinting provide critical tools for individual animal identification and meat product traceability, significantly reducing food fraud risks and enhancing transparency across the supply chain (Zhao et al., 2020). Traceability, alongside attributes like animal welfare and place of origin, enhances consumer trust and satisfaction, thus fostering a safer food supply chain (Chen et al., 2021). The study by Tran et al. (2024) indicates that consumer willingness to pay (WTP) for traceable meat products is significantly higher than for other food categories, highlighting the increasing demand for transparency and safety in animal-derived food products. Additionally, the integration of traceability with other credence attributes, such as organic or animal welfare certifications, further elevates consumer WTP, underscoring the value of a comprehensive traceability system that aligns with consumer preferences and expectations (Tran et al., 2024). The study by Bowling et al. (2008) highlights the use of various devices for animal traceability, such as RFID tags and rumen boluses, across different countries, as well as the challenges associated with information management. Current animal traceability systems face challenges such as the lack of interoperability and integration across different technologies and platforms. This lack of interoperability contributes to heterogeneous business models and ineffective data and knowledge management, which complicates the tracking and management of animals across supply chains (Addo-Tenkorang et al., 2019). The interoperability challenges due to varied technological solutions and standards used by different stakeholders impede seamless traceability across the supply chain (Füzesi et al., 2010).

Challenges in animal traceability in Botswana

In Botswana, the livestock sector plays a critical role in the economy, contributing significantly to food security, employment, and rural development, with beef being the only contributor to foreign exchange earnings from the livestock sector (Bahta et al., 2023). Substantial resources and budget have been allocated to safeguarding the livestock industry, reflecting its critical role in foreign exchange earnings, food security, and the livelihoods of a large segment of the population, while addressing challenges such as productivity stagnation and market exploitation (Van Engelen et al., 2013). The European Union's export requirements mandate stringent monitoring of animal diseases and traceability from farm to fork (European Commission, 2019; European Commission, 2024).

The first animal traceability system introduced in Botswana in 2001 was the Livestock Identification Trace-back System (LITS) (Bowling et al., 2008; Oladele & Jood, 2010). LITS in Botswana utilized RFID technology to electronically tag and track cattle, linking each animal to a central database that recorded its identity, ownership, health status, and location. LITS aimed to enhance cattle traceability, support disease monitoring, and meet European Union export requirements, thereby facilitating access to lucrative international markets and promoting better livestock management practices. Currently, the animal traceability system used in Botswana is the Botswana Animal Identification and Traceability System (BAITS). BAITS serves as a comprehensive platform enabling farmers to systematically record information related to their livestock. It facilitates critical functions such as animal registration, transfer of ownership, tracking the arrival of livestock, documentation of veterinary drug treatments, and reporting the removal of deceased or slaughtered animals. Accessible online, BAITS allows for reporting livestock losses, whether due to natural causes or slaughter, thereby enhancing traceability and management within the livestock sector (Government of Botswana, 2022).

An overview of animal traceability technologies

The paper by Resti et al. (2024) discusses various technologies used in dairy recording tools, including mobile phone applications, desktop applications, web applications, networks, and the Internet of Things (IoT). Mobile phone applications are identified as the most widely used due to their accessibility and ease of use, especially in regions with limited infrastructure. IoT has the potential to automate data collection and provide real-time information, enhancing farm management efficiency. The integration of IoT with other technologies, such as networks and mobile apps, is mentioned as a way to improve the user-friendliness and effectiveness of dairy recording tools. However, challenges related to Internet connectivity and the need for continuous data input are acknowledged as critical factors influencing the successful implementation of these technologies in developing countries.

Pereira et al. (2023) identified various RFID-based methods used for livestock management, animal tracking, traceability, and animal behavior monitoring. Passive UHF RFID tags are the most common, due to their cost-effectiveness and ease of use in tracking cattle and other mammals. RFID is often integrated with other technologies like GPS and cameras to enhance tracking accuracy and provide real-time location data, which is particularly valuable for monitoring animal movement and behavior in large or remote areas. Other integrations include infrared sensors and wireless sensor networks, which help gather additional health and environmental data, facilitating comprehensive monitoring systems. The paper does not propose any new animal traceability technologies but instead reviews the existing methods and their applications in different animal tracking scenarios.

A review paper by Zanetoni et al. (2024) investigates the potential application of blockchain technology in animal product traceability systems, highlighting its emerging role in ensuring food safety and quality. Zanetoni et al. (2024) emphasize that blockchain can provide a decentralized, secure, and transparent method of recording and sharing data across the entire production chain, from farm to consumer. By doing so, blockchain addresses key concerns such as traceability, transparency, and consumer trust, which are increasingly important in food supply chains. The review identifies various use cases where blockchain has been implemented or proposed, such as in the tracking of beef, milk, eggs, fish, and pork, showing its versatility across different types of animal products. However, this review paper does not propose any new blockchain technologies; rather, it compiles existing knowledge and examples from the literature to illustrate the benefits and challenges associated with adopting blockchain for animal traceability.

Hernandez San Juan and González-Vaqué (2020) suggest the use of blockchain technology for enhancing animal traceability within the food supply chain by providing a secure and transparent way to record and verify each step in the production and distribution processes. Blockchain's decentralized ledger system ensures that data related to animal origins, health records, and movement is tamper-proof and easily accessible to all stakeholders, thus improving food safety and quality control. By enabling real-time tracking of animals from farm to fork, blockchain helps meet regulatory requirementsand consumer demands for transparency in the supply chain. The technology's capacity to create a permanent and verifiable record of transactions makes it a reliable tool for preventing fraud and ensuring compliance with food safety standards. Overall, blockchain offers an efficient, scalable, and trustworthy solution for enhancing traceability and accountability in the animal agriculture sector.

García-Infante et al. (2024) investigated the effectiveness of machine learning algorithms as tools for meat traceability, specifically to classify Spanish Mediterranean lamb carcasses based on production systems. The study evaluated six different algorithms, namely, artificial neural networks (ANNs), decision trees, k-nearest neighbors (KNN), naive Bayes, multinomial logistic regression, and support vector machine (SVM), using datasets that include organoleptic, sensory, and nutritional traits of lamb meat. The ANN and SVM algorithms demonstrated the highest accuracy in categorizing lamb production systems, with ANN achieving accuracy scores of up to 0.88. In contrast, the KNN algorithm showed the lowest performance, with accuracy scores of 0.54 or lower. The study highlights the potential of machine learning tools to enhance the traceability and classification of meat products, suggesting that their use can improve transparency and consumer confidence in the meat industry. Using machine learning algorithms to enhance meat traceability aligns with our research's goal of improving animal traceability systems, by demonstrating the importance of advanced technological tools for ensuring food safety, quality, and consumer trust.

Gbashi and Njobeh (2024) explored the potential application of artificial intelligence (AI) and machine learning (ML) for enhancing food integrity and, specifically, animal traceability. The authors examine how AI and ML can automate and improve the accuracy of tracking and monitoring livestock movements, health status, and environmental conditions. The review highlights various AI and ML techniques, such as predictive analytics, image recognition, and anomaly detection, that could optimize data collection and decision-making processes in animal traceability. The paper also discusses the integration of these technologies with existing systems to enhance data management, provide real-time insights, and improve food safety and disease outbreak response. do not develop any new technologies for animal traceability based on AI and ML; instead, they focus on reviewing existing research.

Navia et al. (2024) reviewed various sensor technologies used for monitoring the vital signs of livestock, emphasizing applications that enhance animal health and welfare. The study identified long-range communication technologies such as LoRaWAN as the most common for transmitting data from sensors monitoring parameters like movement, geo-location, body temperature, and heart rate. Short-range technologies like Bluetooth and WiFi are also used, often in combination with long-range systems for better coverage. The paper suggests opportunities for developing more comprehensive sensor solutions that enhance traceability by providing continuous location data and robust communication capabilities. It also emphasizes the need for integrating energy-harvesting technologies to improve the autonomy and sustainability of these traceability systems.

León et al. (2024) evaluated the effectiveness of handheld near-infrared spectroscopy (NIRS) as a non-destructive tool for traceability and authentication of the aging process in Angus beef steaks. Using partial least squares-discriminant analysis, the study demonstrates high accuracy in distinguishing between aged and non-aged beef and predicting refrigeration storage times, with over 90% accuracy in external validation. This research suggests that NIRS technology could be valuable in digital transformation strategies for meat supply chain traceability, ensuring product authenticity and enhancing consumer trust. The paper highlights the importance of advanced, non-destructive technologies for ensuring authenticity and enhancing traceability, which aligns with our goal of developing interoperable and standardized traceability systems for the livestock sector.

Animal traceability frameworks

Füzesi et al. (2010) proposed a framework for animal traceability. The study introduces the concept of a digital business ecosystem (DBE) as a potential solution to improve traceability and information exchange in the meat industry. The DBE framework is designed to create an Internet-based environment where businesses can efficiently interact, share data, and implement traceability methods. This approach emphasizes using modern technologies like barcodes, RFID, and XML-based data sharing to ensure continuous and reliable traceability across different stages of the meat production and supply chain. The DBE framework aims to address interoperability challenges and promote standardized practices, which are essential for effective animal traceability.

The framework for animal traceability by Bai et al. (2017) is structured around key components, including the identification of traceable resource units (TRUs), a centralized database to store and manage data related to these TRUs, and an information flow mechanism that facilitates the collection, processing, and inquiry of traceability information. The framework aims to ensure effective tracking of animals from their origin to the final product, enhancing transparency and compliance with health and safety regulations.

Marinello et al. (2017) presented a framework for a traceability system specifically designed for the animal product supply chain using blockchain technology. This framework aims to enhance the transparency, security, and efficiency of tracking animal products from their origin to the end consumer. By utilizing blockchain's decentralized and immutable nature, the proposed framework ensures that data related to animal health, feed, and movement is securely recorded and easily accessible by all stakeholders in the supply chain, including farmers, regulators, and consumers. This approach is intended to improve food safety, comply with regulatory requirements, and increase consumer trust by providing verifiable and tamper-proof information.

Addo-Tenkorang et al. (2019) proposed a conceptual framework for advanced animal traceability using Internet of Things (IoT) technologies to enhance supply chain management. The framework integrates RFID technology, solar-powered electronic tags, GPRS, GSM, and Google Earth to track animal health, birth records, ownership history, and location. By employing a cloud-based architecture, the framework aims to provide a low-cost solution for farmers, addressing vulnerabilities such as stock theft, straying animals, and inadequate health management. This IoT-driven approach promises to improve visibility and data transmission across the supply chain, contributing to better management practices in animal husbandry. The proposed system highlights the potential for digitization to add value to agricultural businesses, especially in free-ranging environments in Africa.

Chen et al. (2019) presented a mobile solution for pork traceability using 2D barcode technology, focusing on improving food safety and quality in China's pork supply chain. The system enables the collection, transformation, and delivery of traceability information from breeding to retail, integrating seamlessly with government supervision systems. It offers a cost-effective alternative to RFID by utilizing batch-based traceability rather than individual animal tagging, making it accessible for smaller-scale operations common in China. The implementation in Jilin Province demonstrated enhanced transparency and credibility of pork traceability, promoting consumer confidence and regulatory compliance. This approach is relevant to our research on animal traceability technologies as it illustrates the successful application of mobile and barcode technologies to create an effective and scalable traceability system.

A framework for animal identification and traceability using AI-based muzzle recognition technology utilizes deep learning algorithms and convolutional neural networks to analyze unique muzzle patterns of bovine animals, providing an accurate and cost-effective alternative to traditional methods like ear tags (Girish et al., 2020). Key components of the framework include muzzle detection, face alignment, feature extraction, and pattern recognition, which collectively enable the precise identification of animals. The system integrates a mobile application interface for capturing and uploading images, along with a MySQL database to store image links and identification numbers, ensuring efficient data management and verification. By leveraging open-source technologies and ensuring cross-browser compatibility, the proposed framework offers a scalable and field-friendly solution for enhancing animal traceability in various applications such as farm management, disease control, and livestock insurance.

A "butcher-to-farm" traceability framework designed for smallholder pig systems in Western Kenya aims to enhance disease control, food safety, and production efficiency (Mutua et al., 2020). This framework integrates the use of coded plastic ear tags to uniquely identify pigs, with records of pig movements, health events, and sales maintained by farmers, traders, and slaughterhouse operators. The system integrates data capture and database management technologies to ensure accurate tracking from the farm through to the slaughterhouse and butcher shops. It emphasizes the importance of involving local veterinary authorities and stakeholders to implement and maintain the system effectively. The traceability framework is intended to facilitate early detection and containment of diseases like African swine fever and cysticercosis, thereby improving public health and potentially opening new market opportunities for smallholder farmers.

A conceptual framework for animal traceability, suggested by Mwanga et al. (2020) as a result of a literature review, integrates various components, including electronic record-keeping, RFID technology, and mobile devices, to track and manage livestock data effectively. It involves a centralized system that allows data collection at the farm level, which is then transmitted to local and national databases for comprehensive tracking. RFID tags and sensors are used to monitor animal movements, health, and other critical information, enhancing traceability from farm to fork. The framework also incorporates mobile applications for farmers to input and access data easily, facilitating real-time decision-making and compliance with international traceability standards. This integrated approach aims to improve disease control, food safety, and marketability of livestock products by ensuring accurate and reliable animal identification and record-keeping throughout the supply chain.

Tripoli and Schmidhuber (2020) introduced a framework for optimizing animal traceability using digital technologies like IoT, blockchain, AI, and big data analytics to enhance efficiency, accuracy, and security. The framework includes electronic identification (EID) methods and digital ledger technologies (DLTs) to securely store and share data across the supply chain. AI and predictive analytics are used for monitoring animal health, detecting diseases, and ensuring compliance with food safety standards. The framework also emphasizes the need for supportive policies, infrastructure, and capacity building to facilitate the adoption of these technologies. Together, these components aim to improve animal health management, ensure food safety, simplify trade, and raise consumer awareness.

Arvana et al. (2023) proposed a blockchain-based framework for animal traceability in the agri-food sector, focusing on the production of Portuguese hams. The framework utilizes a multi-layer architecture that includes a business layer to define the supply chain processes, an integration layer for data collection and sharing, a cloud computing layer incorporating blockchain technology for decentralized and immutable data storage, and an application layer for user interaction. Smart contracts are employed to automate the recording and validation of transactions, ensuring data reliability and transparency throughout the entire product lifecycle. The system enhances traceability by capturing detailed information at each stage, from the animal's origin to the final consumer, making the process more transparent and trustworthy. This approach addresses the limitations of traditional centralized traceability systems, reducing the risk of data tampering and increasing consumer confidence in the quality and safety of meat products.

A framework for integrating digital twins (DT) of livestock production into a unified digital platform for agricultural management is proposed by Medennikov (2024). This framework emphasizes using digital twins to model and monitor various aspects of livestock farming, such as feeding, milking, and breeding, ensuring precise traceability and management. The DT framework includes cloud-based sub-platforms for collecting and storing primary data, technological databases for managing farming operations, and a knowledge base for algorithmic management and decision-making. By integrating these components, the framework aims to create a holistic system that connects livestock production with other agricultural sectors like crop production and processing. The unified approach seeks to improve sustainability, enhance breeding practices, and meet global standards for food safety and environmental protection

A framework for integrating blockchain technology into animal healthcare by Walunj and Gourkar (2024) utilizes a permissioned blockchain platform, specifically Hyperledger Fabric, to manage various aspects of animal health data securely and transparently. The proposed framework involves a system design that includes multiple nodes representing authorized entities, such as veterinary clinics, adoption centers, and emergency services, with each node authenticated through a Membership Service Provider (MSP). Smart contracts are utilized within this framework to enforce business rules and access control policies, ensuring that only authorized personnel can update or view specific types of data. This approach aims to enhance privacy, trust, and the traceability of animal health records, contributing to better management of animal healthcare.

Witt et al. (2024) proposed a framework to validate the use of slaughterhouse indicators as proxies for on-farm animal welfare and health assessments in pigs. It integrates data collected from 12 on-farm and seven slaughterhouse indicators, combining them into three health indices: limb health, other organ health, and respiratory health. The study examines the agreement between these indices across different production stages, such as farrowing, rearing, and fattening, to determine the feasibility of using slaughterhouse findings as retrospective indicators of on-farm conditions. The research shows that while some slaughterhouse indicators can partially substitute on-farm assessments, complete replacement is not feasible, and agreement varies with the timing of assessments. Although this framework does not currently incorporate ontologies, an ontology-driven approach, as proposed in our current study, could significantly enhance data integration, consistency, and semantic interoperability, leading to more robust and scalable animal welfare monitoring systems.

Gaps identified in existing studies

The existing studies reveal several gaps in the application of advanced technologies in the area of animal traceability. The first identified gap is the insufficient focus on integration challenges. While there is acknowledgment of the potential benefits of integrating IoT with mobile apps and networks (Resti et al., 2024), there is limited practical guidance or frameworks on how to effectively implement these integrations, especially in regions with poor Internet connectivity and infrastructure. The second gap is the lack of research on the economic feasibility of the proposed advanced technologies. Many of the technologies discussed, such as IoT, RFID, and blockchain, may face barriers to adoption due to their cost and the lack of incentives for farmers in developing countries to implement these systems. More research is needed to explore cost-effective solutions and economic models that can encourage the widespread adoption of traceability technologies. The last and most important gap is the lack of discussion on data standardization and interoperability. Despite the advances in traceability technologies, there is a noticeable absence of discussion on standardization and interoperability of data across different traceability tools and platforms, which is crucial for achieving seamless integration and effective traceability across various stages of the supply chain.

In addition to the identified gaps in the publications on the use of advanced technologies in animal traceability, there are gaps identified in existing animal traceability frameworks. The first gap is scalability and cost-effectiveness. While several frameworks, such as those using IoT (Addo-Tenkorang et al., 2019) and blockchain technology (Marinello et al., 2017; Arvana et al., 2023), promise enhanced traceability and transparency, they often face challenges in scalability and cost-effectiveness, particularly for smallholder farmers in developing regions. There is a lack of practical solutions that balance high-tech capabilities with affordability and ease of use for broader adoption. The second gap is integration and interoperability. Existing frameworks, like the DBE proposed by Füzesi et al. (2010) and the centralized database systems by Bai et al. (2017), emphasize the importance of data sharing and interoperability. However, there is a need for more comprehensive strategies to integrate various technologies (e.g., RFID, blockchain, mobile apps) into a unified system that ensures seamless interoperability across different platforms and stakeholders, including farmers, regulators, and consumers. The third gap is data privacy and security. Blockchain-based frameworks (Marinello et al., 2017; Arvana et al., 2023) address data security and transparency. However, there is limited discussion on managing data privacy concerns, especially when handling sensitive information related to animal health and owner details. There is a gap in frameworks that offer robust security measures while also maintaining privacy and confidentiality of data. The fourth gap is regulatory and policy support. Several frameworks mention regulatory compliance as a benefit of traceability systems (Chen et al., 2019; Tripoli & Schmidhuber, 2020). However, there is a gap in frameworks providing detailed guidance on aligning these systems with varying international and local regulations. More comprehensive frameworks are needed that include specific policy recommendations and implementation strategies to ensure compliance across different regions.

The study rationale

The gaps identified in existing studies highlighted opportunities for future research and development to create more inclusive, secure, scalable, and interoperable animal traceability frameworks that consider the economic, social, and technological challenges faced by stakeholders in various settings.

This research aimed to address the existing gap in interoperable, knowledge-based frameworks for developing animal traceability systems and related platforms in Botswana. The lack of interoperability has undermined the effectiveness of promising initiatives like LITS and BAITS. While these systems have succeeded in gathering animal traceability data, they did not offer a standardized and interoperable framework that fully integrated all relevant stakeholders. Currently, these systems mainly serve only two categories of stakeholders (government and farmers), despite the involvement of at least five different categories of stakeholders, as demonstrated by our research, in the animal traceability process. There is a pressing need for a truly interoperable system that brings all stakeholders together within a unified environment, allowing them to access critical information more efficiently, without the constant need for veterinarian intervention for every cattle-related matter. Such a system should support reliable cattle identification through advanced tracking technologies that automatically feed data into the platform. It should also provide user-friendly interfaces in both Setswana and English, reducing reliance on technical terminology. Moreover, a centralized database would enhance the generation and updating of reports, significantly reducing processing times. By promoting data sharing and reuse, this interoperable system would increase the value of collected data, leading to more efficient and effective animal traceability.

This study proposes an ontology-driven framework for animal traceability (ODF-AT) in Botswana, which can be extended to other developing countries. The framework focuses on enhancing interoperability and integration among stakeholders in the livestock sector through ontology-based knowledge management. It is structured into four layers: an input layer for data collection, a semantic core layer for query processing, a knowledge management layer serving as a data hub, and an application layer for user interaction. This framework addresses gaps in scalability, data privacy, and standardization, aiming to improve disease control, food safety, and economic outcomes by providing a comprehensive animal traceability system.

Objectives of this research were stated as follows:

RO1: To identify and analyze the limitations and challenges of current animal traceability frameworks and systems in Botswana.

RO2. To design and develop an ontology-driven framework for animal traceability (ODF-AT) that enhances interoperability, integration, and knowledge sharing among stakeholders in Botswana's livestock sector.

RO3. To evaluate the feasibility and effectiveness of the proposed ontology-driven framework in addressing challenges related to disease control, food safety, and economic outcomes in Botswana.

RO4. To create a scalable and adaptable framework that can serve as a model for implementing animal traceability systems in other regions or developing countries.

The following research questions were derived from the stated research objectives:

RQ1. What are the specific limitations and challenges of current animal traceability systems in Botswana, such as BAITS and LITS, that hinder their effectiveness?

RQ2. What are the key components of an interoperable and knowledge-driven framework for animal traceability in Botswana?

RQ3. How can an ontology-driven approach address the challenges of interoperability and integration in animal traceability systems?

RQ4. What is the impact of the proposed ontology-driven framework on stakeholders' collaboration, data sharing, and overall efficiency in the livestock sector?

RQ5. How can the framework be adapted and scaled for application in other regions with similar challenges in animal traceability?

All the stated research objectives were successfully achieved, and the research questions comprehensively answered in this study.

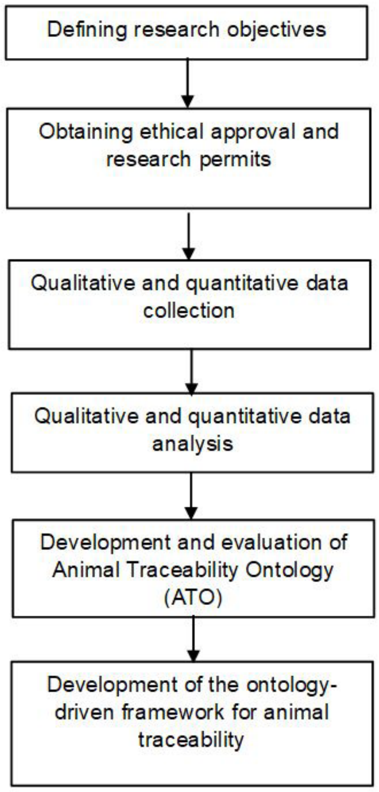
The rest of the paper is organized as follows. Section 2 details the methodology used for developing the ontology-driven framework for animal traceability (ODF-AT). Section 3 presents the results and discusses the findings. Finally, Section 4 concludes the paper and suggests future research directions.

Materials and methods

This study employed both qualitative and quantitative methods to explore and describe user experiences and the current functionality of animal traceability systems in Botswana (Cresswell & Plano Clark, 2018; Cresswell & Cresswell, 2022). An explanatory research design was adopted, allowing for a comprehensive examination of the challenges and opportunities within animal traceability.

An ethical clearance certificate (HREC-011) was obtained from the research ethics committee at Botswana International University of Science and Technology (Botswana). Additionally, research permits were secured from the Ministry of Agriculture (DVS 7/4/1 VII (90)) and the Ministry of Communications, Knowledge, and Technology (MCKT/1/11/1 I (38)) to authorize interactions with stakeholders.

Data was collected using face-to-face interviews and structured questionnaires, targeting five key categories of stakeholders, including farmers, veterinary professionals, local administrative authorities, officials from the Ministry of Agricultural Development and Food Safety, and representatives from the Botswana Meat Commission. The research involved interviewing various stakeholders to gather comprehensive insights into animal traceability practices. Farm owners and managers were interviewed to provide practical insights into the current animal traceability practices used in the field. Veterinary representatives were consulted to detail the specific tasks they perform related to animal traceability, including health monitoring and documentation. Representatives from the local administrative authorities were engaged to explain the Matimela program (i.e., the management of stray cattle in Setswana), a government initiative aimed at managing stray animals, and its role in traceability efforts. The Ministry of Agricultural Development and Food Safety was involved in providing in-depth information on the BAITS, highlighting its implementation and functionality. Finally, representatives from the Botswana Meat Commission discussed the cattle market dynamics and related systems, offering a broader perspective on the traceability framework within the livestock industry. The purposive stratified sampling method ensured representation across the nine districts of Botswana, with a final sample size of 66 participants. The research process is outlined in Figure 1.



Source: Own elaboration

Figure 1: Steps followed in this research.

In *the data collection stage*, mixed methods were employed to gather qualitative and quantitative data from stakeholders. Data collection tools included semi-structured interviews and questionnaires, targeting a diverse group of participants across the nine districts of Botswana. The collected information was related to current practices, challenges, requirements, and user experiences related to animal traceability.

In *the data analysis stage*, qualitative data was analyzed using content and thematic analysis techniques, facilitated by NVivo 12 software, to identify key themes and patterns. Quantitative data was analyzed using descriptive statistical methods in Microsoft Excel to quantify stakeholder perspectives and challenges.

The next stage involved *the development of the animal traceability ontology* which was at the core of the proposed ontology-driven framework. An ontology defines a common vocabulary for researchers who need to share information in a domain, providing machine-interpretable definitions of basic concepts and the relationships between them (Atanasova, 2011). The ontology was developed using METHONTOLOGY (Fernández-López et al.,

1997) and the Protégé ontology development environment. This involved defining concepts, relationships, data properties, and object properties relevant to animal traceability. The ontology design focused on semantic consistency, scalability, and reusability, allowing for the integration of various data sources and supporting multi-language functionality.

The development of the ontology-driven framework for animal traceability was guided by the critical thinking approach. Critical thinking was a core component of the research design, guiding the linkage and analysis of the OD-FAT components (Heard et al., 2020; Paul & Elder, 2020). A critical thinking approach involves systematically evaluating information, identifying patterns, and making informed decisions based on evidence and logical reasoning. By applying critical thinking, one can analyze complex data sets, draw connections, and develop coherent frameworks that address specific problems effectively. In the context of developing an ontology-driven framework for animal traceability, critical thinking was essential for dissecting the relationships between various elements of the system, ensuring that the framework is both comprehensive and practical. This process involved incorporating both the collected data and external data sources to ensure a comprehensive and well-rounded analysis.

In this study, project maps generated by NVivo were utilized to identify patterns and relationships within the collected data, which were crucial for developing the ontology-driven framework (Wilson & Bruni-Bossio, 2020). This method provided a structured visual representation of data, depicting parent and child relationships among key concepts, such as *Farming, Cattle Market, Records*, and *BAITS system*. By illustrating these concepts and their interconnections, the project maps facilitated the identification of possible structures that could inform the ontology-driven framework. The analysis involved linking main concepts to the codes generated per district, enabling a comprehensive understanding of the data and informing the decision-making process for the overall functionality of the proposed framework.

Results and discussion

Results and discussion of the quantitative data collection and analysis

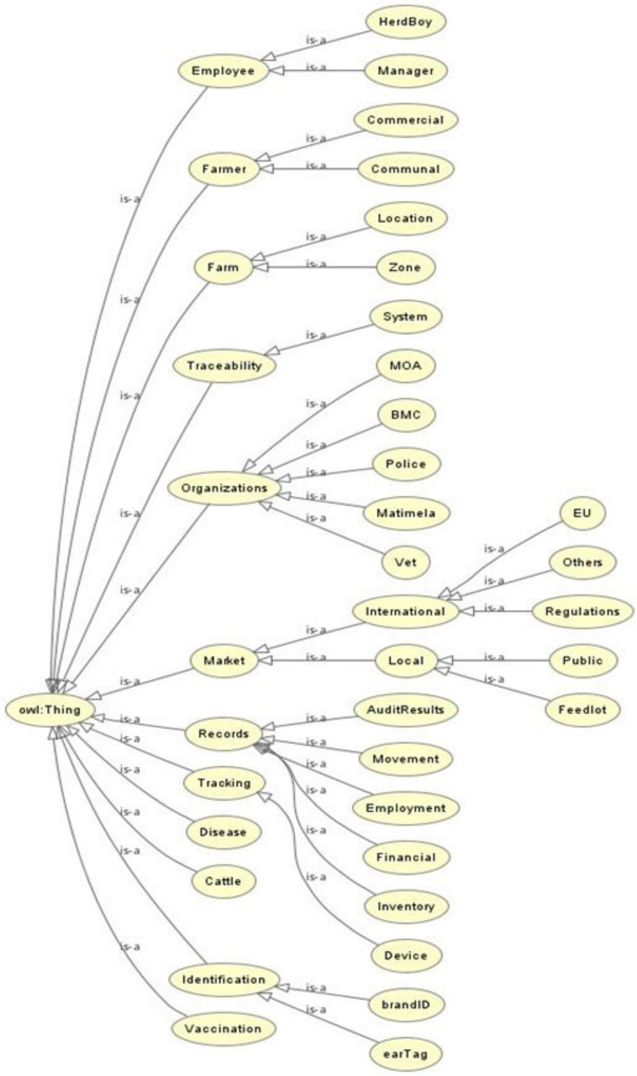
The findings from the collected and analyzed quantitative data centered on respondents' perceptions of the challenges related to animal traceability in Botswana. Participants were asked to rate their perceptions on various aspects of animal identification, tracking, and traceability methods. More than half of participants (55%) indicated that the current methods used by farmers are inadequate, despite 42% making efforts to address these issues. Farmers' associations, established to support various agricultural activities including traceability, were criticized for their ineffectiveness; 56% of respondents expressed that these associations were more about talk than action.

The Matimela program, a government initiative designed to manage stray cattle and prevent theft by housing unclaimed animals in kraals, was also viewed negatively. A significant 85% of respondents believed that the program was ineffective, mainly due to the policy of auctioning unclaimed cattle after 15 days without offering compensation to rightful owners. This has led to dissatisfaction among farmers who often found their cattle sold off without proper notification.

Regarding the BAITS, only 17% of respondents found it useful for identifying cattle, especially in cases where ear tags were still intact. However, 39% felt that BAITS was largely ineffective because enforcement officers and Matimela program administrators rarely utilized it to trace cattle ownership. Consequently, 67% of respondents believed that law enforcement was not doing enough to combat cattle theft. Furthermore, 44% of respondents expressed uncertainty about the usefulness of BAITS, viewing it primarily as a tool for purchasing ear tags and transferring cattle ownership rather than a comprehensive traceability solution.

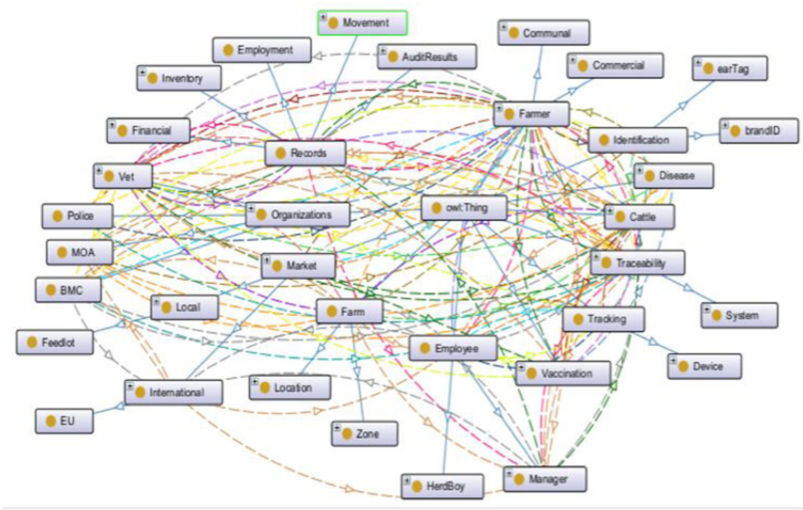
Results and discussion of the animal traceability ontology development

The animal traceability ontology (ATO) was developed as part of the ontology-driven framework for animal traceability in Botswana to address the challenges of non-interoperable animal traceability systems in Botswana by enhancing communication and data exchange among stakeholders. Stakeholders such as farmers, veterinarians, and regulatory bodies contributed insights that helped refine the ontology to meet real-world needs and practices. The ontology was structured to facilitate knowledge sharing and reusability, supporting efficient tracking and monitoring of cattle. Visualization tools, such as Protégé OWLViz and OntoGraf were used to map out the relationships among different entities, making the ontology easier to understand and implement (Figures 2 and 3).



Source: Own elaboration

Figure 2: Visualization of the ATO with Protégé OWLViz.



Source: Own elaboration

Figure 3: Visualization of the ATO with Protégé OntoGraf.

The ATO was found to be logically sound and free from inconsistencies, ensuring its reliability for practical applications. The evaluation showed that the ATO had a robust structure with rich relationships, making it suitable for detailed traceability tasks. When compared with a reference ontology, Animal Health Ontology (Data-Driven Surveilance, 2024), the ATO demonstrated higher specificity and alignment with the needs of animal traceability, proving its effectiveness in real-world scenarios. Overall, the ATO enhanced the ability to manage, monitor, and track livestock efficiently, supporting knowledge-driven economic opportunities.

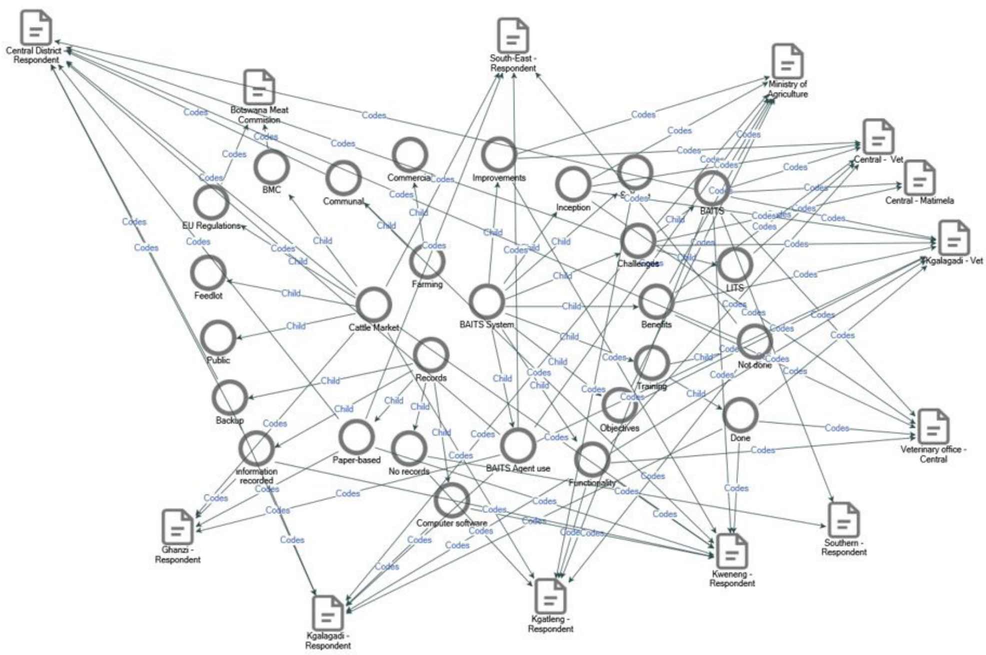
The ATO is not the primary focus of our current paper; it was considered only as one component of the proposed ontology-driven framework for animal traceability in Botswana. The complete ATO is available in Figshare (https://figshare.com/articles/dataset/AnimalTraceability_rdfAnimal_Traceability_Ontology/24461224?file=42977926).

Results and discussion of the development of the ontology-driven framework for animal traceability (ODF-AT) in Botswana

NVivo project maps were employed in this study to uncover patterns and relationships within the data, which informed the development of the ontology-driven framework. These visual maps were instrumental in outlining the overall functionality and decision-making processes of the framework, as they provided a clearer picture of how different concepts are interconnected. As highlighted by Wilson and Bruni-Bossio (2020), visual project mapping effectively represents logical and cognitive processes, making it a valuable tool in structuring this study's framework. One example of the project map in Figure 4 depicts parent-child relationships essential for understanding the complex interactions within the animal traceability domain. By visualizing the main concepts, such as Farming, Cattle Market, Records, and BAITS system, alongside their associated child relationships, the project map facilitated a comprehensive view of the data. This visualization also linked the main concepts to specific codes generated from district-level data, providing deeper insights into regional variations in traceability practices.

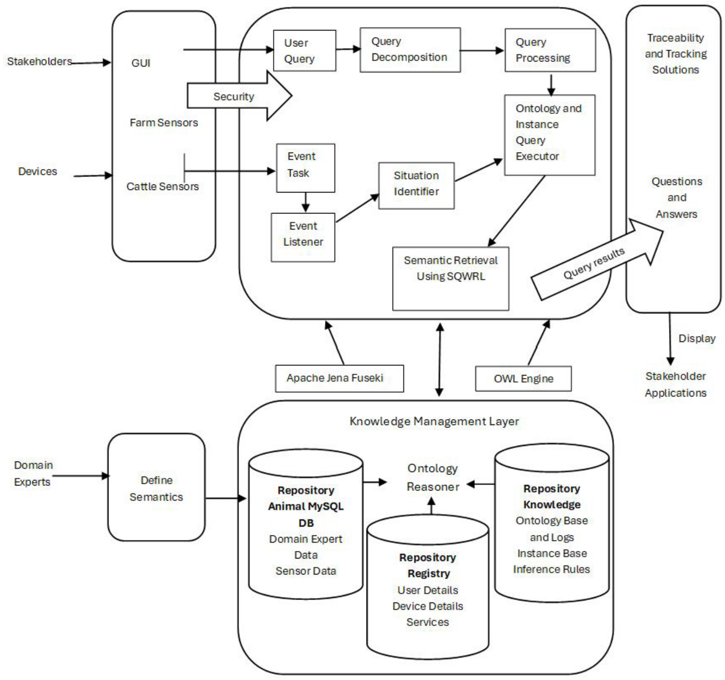
These visualizations contributed to the development of the ontology-driven framework by organizing data relationships, which will ultimately enhance data sharing and interoperability.

Figure 5, presenting the ontology-driven framework for animal traceability, illustrates the guiding principles for building systems, websites, applications, and databases related to animal traceability.



Source: Own elaboration

Figure 4: A project map illustrating the four main concepts within the animal traceability domain (*Farming, Cattle Market, Records,* and *BAITS system*) and their coding relationships across different districts.



Source: Own elaboration

Figure 5: The ontology-driven framework for animal traceability in Botswana.

This framework offers a standardized, integrated, semantic approach to managing traceability data, addressing the evolving challenges in the field. Comprising four layers − input, semantic core, knowledge management, and application − the framework facilitates seamless data flow and knowledge management.

The input layer of the ODF-AT

The input layer is supplied by several sources. The first source consists of stakeholders who directly input data or submit queries via the graphical user interface. These stakeholders include farmers, veterinarians, the Ministry of Agricultural Development and Food Safety, the Botswana Meat Commission, Matimela officers, and police officers. Another source of input is sensor devices placed on cattle and farms, which monitor conditions and trigger alerts. Information and alerts generated by these devices feed into the input layer, providing real-time data. The final source of input comes from domain experts specializing in animal traceability, who contribute valuable insights that are directed to the knowledge management system.

Farm location and the surrounding environment significantly influence the development of the system. These factors determine the type of sensor devices suitable for use in specific areas. Farmers often face challenges in using certain systems due to the remote locations of their farms, which may lack Internet connectivity. Developers should consider designing systems that can function with satellite technology to accommodate these remote areas. The type of farm − commercial or communal − also affects sensor device choices and system priorities. Commercial farms focused on business objectives, have different requirements compared to communal farms that rear cattle for family sustenance. Communal farmers often need tracking sensors more urgently because their cattle graze freely and are more vulnerable to theft. In contrast, commercial cattle typically graze within enclosed areas, allowing for easier monitoring and management. Commercial farmers can use sensors for counting livestock, monitoring health and behavior, tracking heat periods, and managing disease control. While these sensors are equally beneficial to communal farmers, they especially require tracking devices to prevent theft. Currently, Botswana's animal traceability system does not incorporate sensor devices to capture critical cattle-related data.

The semantic core layer of the ODF-AT

Within the semantic core layer, the process begins with a security authentication check for users logging into the system. This check ensures the protection of stakeholders' private information and determines user identity and access privileges.

Each user has specific viewing and editing rights within the system. If a user is authorized, their query advances to the next layer for processing; otherwise, an error message is returned. In this layer, user queries and device-generated alerts are handled. Each user query is first registered in the system, and query processing begins by breaking down the query from a high-level format into a relational algebra query. The query undergoes checks for semantic and syntactic correctness, involving semantic analysis, simplification, and restructuring.

The decomposed query is then processed by the query processor, which forwards it to the ontology query executor for verification. The ontology query executor follows a four-step process. It first checks the cache for an existing execution plan. If no plan exists, the query parser sends it through the semantic retrieval tree, using SQWRL to access the knowledge management layer. SQWRL acts as the query language, defining SQL-like operations for the ontology query executor. It constructs specifications for retrieving information stored in the ontology base. This method of semantic retrieval leverages ontological properties, concepts, instances, SQL statements, and production rules. Through this setup, the animal traceability system effectively aligns user query intentions with the knowledge base, ensuring accurate and relevant information retrieval.

The knowledge management layer of the ODF-AT

The knowledge management layer includes the MySQL database repository, the ontology reasoner, and the ontology base with associated logs. This layer is designed to describe complex situations and their related animal traceability concepts. The first repository stores data from sensor devices and input from domain experts, capturing all raw information. MySQL is used to transform this raw data into more structured and organized information for better management and analysis. The second repository houses the ontology base and logs, where ontologies are stored as OWL files, managed by administrators, and used to deduce relevant knowledge. This repository also contains instances representing various concepts such as OWL files, electronic documents, and HTML pages, which are crucial for developing new ontology constructs and making decisions about modifying existing constructs.

Ontology logs within the repository track actions and operations performed on the ontologies, serving as a tool for recovering from data or system corruption and inconsistencies. Recovery processes involve reviewing uncommitted queries in the logs and rolling back changes as necessary. The third repository includes registries for user details, device details, and services. The user details registry provides semantic descriptions of users' profiles and preferences, while the device details registry offers information about sensor device status and configurations. The service registry supplies functional services based on the location and context of service deployment, linking events with appropriate action services.

The ontology reasoner, also known as the semantic rules engine, infers logical consequences from axioms defined in OWL. It handles query answering by evaluating knowledge representations in the ontology against inputs from animal traceability repositories. Initially, the reasoner checks if the ontology structure meets the specified axioms; if not, it issues a warning message. If the structure is valid, the reasoner proceeds to retrieve query results based on inference rules. The reasoner converts user requests into SQWRL query statements and returns results to the user. This process ensures that the animal traceability model remains logically consistent and reliable.

Apache Jena Fuseki is a SPARQL server that can function as a standalone server or an operating system service. SPARQL, a standard for querying and updating, allows users and developers to focus on the information they seek rather than database organization. Apache Jena Fuseki supports semantic web applications by facilitating efficient information retrieval and management. The OWL Engine works alongside the ontology reasoner to handle animal traceability queries, establishing protocols for communication between users and the system, and managing responses based on knowledge representation.

The application layer of the ODF-AT

The results of the query processed within the knowledge management layer are then forwarded to the application layer. The application layer computes these results and presents them to stakeholders through the graphical user interface (GUI), functioning as the final output phase. This layer showcases the developed systems and applications, which are delivered to users, allowing them to interact with the system through the GUI. As illustrated in Figure 5, this outcome phase is directly connected to stakeholders, who serve as the end users of the system.

A critical consideration is the language used by the system for communication. In Botswana, existing systems face language barriers as most users are more comfortable with the native language, Setswana, whereas the systems typically communicate in English. To address this issue, developers should implement bilingual support, offering communication in both Setswana and English to accommodate all users. Once the system has been tested and finalized, it should be deployed with comprehensive documentation and user manuals. Conducting training sessions for users is essential, as the lack of adequate training has been a shortcoming in current systems in Botswana. These training courses will help users understand and utilize the system effectively. Moreover, training sessions provide an opportunity for developers to identify any issues and make necessary adjustments early on. Ongoing maintenance is crucial to ensure the system remains functional and up to date, with regular updates and fixes implemented as part of this ongoing support process.

Conclusion

Key findings and their alignment with research objectives and questions

This study introduced an ontology-driven framework for animal traceability (ODF-AT) in Botswana to address key challenges of interoperability, integration, and standardization in existing systems. By incorporating advanced technologies such as ontology-based knowledge management, sensor devices, and secure data processing, the framework ensures efficient and reliable livestock traceability from farm to fork. It effectively addresses gaps in scalability, data privacy, and standardization, offering potential improvements in disease control, food safety, and economic outcomes for Botswana's livestock sector.

The research objectives were successfully met, beginning with the identification and analysis of limitations in current animal traceability systems, such as BAITS and LITS. Using a combination of literature review, semi-structured interviews, and structured questionnaires with stakeholders—including farmers, veterinarians, government officials, and Botswana Meat Commission representatives—the study identified challenges such as poor interoperability, limited stakeholder engagement, and inadequate use of tracking technologies.

The second objective, the design of the ODF-AT, was achieved using the METHONTOLOGY methodology and the Protégé development environment. Insights from stakeholders and literature informed the creation of a four-layer framework—input, semantic core, knowledge management, and application—ensuring seamless integration and data interoperability. The framework integrates advanced features, including real-time data processing and user-friendly interfaces.

The third objective evaluated the framework’s feasibility and effectiveness. Logical consistency checks and comparative analysis validated the Animal Traceability Ontology (ATO), a core component of the framework, ensuring alignment with practical needs. Stakeholders confirmed that the framework enhances communication and data sharing, addressing critical traceability challenges.

The final objective focused on scalability and adaptability. The framework’s modular design supports integration with various technologies and contexts, enabling application in other regions and for additional livestock or agricultural products. Future research directions suggest tailoring the framework to local needs, including multi-language support and cost-effective technologies.

The study also answered key research questions. It identified limitations in current systems, such as lack of interoperability, inadequate technology use, and insufficient enforcement mechanisms. It outlined essential framework components, demonstrated how ontology-driven approaches address integration challenges, and highlighted the framework’s positive impact on collaboration, data sharing, and operational efficiency. Lastly, it detailed the framework's adaptability for other regions with similar traceability challenges.

Overall, this study achieved its objectives and provided a comprehensive solution to enhance animal traceability in Botswana and beyond.

Implications for theory, policy, and practice

Theoretically, this research highlights the value of ontology-driven frameworks in addressing challenges related to interoperability, integration, and data standardization in complex systems. The proposed framework demonstrates how advanced knowledge management techniques can enhance traceability processes, providing a structured approach that aligns with evolving technological and methodological advancements.

From a policy perspective, the study emphasizes the importance of regulatory frameworks that support the adoption of interoperable and scalable systems. It underlines the need for policies that address data privacy, stakeholder collaboration, and infrastructure development, ensuring alignment with international trade requirements and food safety standards. These insights can guide policymakers in creating supportive environments for implementing traceability systems.

Practically, the study provides a scalable and adaptable framework for improving animal traceability in Botswana and similar contexts. It incorporates advanced technologies such as sensor devices and knowledge management tools to enhance real-time data collection and processing. The framework's emphasis on user-friendly interfaces and multilingual support ensures accessibility for diverse stakeholders. By addressing gaps in current systems, the research contributes to improving disease control, food safety, and economic outcomes, offering a practical solution for stakeholders across the livestock sector.

Study limitations and future research

Despite the promising results, this study has several limitations that highlight opportunities for future research. First, the ODF-AT framework is tailored to the Botswana context, and its applicability in other developing regions with distinct socio-economic and environmental conditions may require significant adjustments. Future research should focus on customizing and adapting the framework for use in diverse settings, conducting comparative studies to assess its adaptability and effectiveness across different contexts.

Second, the deployment of advanced technologies, such as ontology-based knowledge management and sensor devices, faces practical challenges in rural and remote areas of Botswana. Limited Internet connectivity, inadequate infrastructure, and high technological costs could hinder full-scale implementation. Addressing these issues calls for exploring alternative solutions, such as satellite-based communication systems, and developing affordable sensor devices that cater to small-scale farmers. Partnerships with technology providers and government agencies could facilitate these advancements.

Third, the study's focus on cattle reflects its economic and food security significance in Botswana, but the framework's potential for broader agricultural applications remains unexplored. Expanding the framework to include other types of livestock and agricultural products would create a comprehensive traceability solution, supporting food safety and quality across various sectors. Collaborative efforts with experts from different agricultural domains are essential for refining the framework to meet diverse stakeholder needs.

Fourth, while the framework incorporates security and data privacy measures, continuous updates are needed to counter evolving cybersecurity threats. Implementing advanced encryption techniques, multi-factor authentication, and regular security audits would enhance data protection and compliance with privacy regulations. Future work should prioritize collaborations with cybersecurity experts to strengthen the framework's resilience.

Fifth, the success of the ODF-AT depends heavily on stakeholder engagement and cooperation. Resistance to change, lack of awareness, and limited technical expertise may pose barriers to adoption. Comprehensive training programs and awareness campaigns tailored to various stakeholder groups are crucial for addressing these challenges and ensuring active participation. Building a strong network of informed and collaborative stakeholders will enhance the framework's acceptance and functionality.

Lastly, while the study's evaluation of the ODF-AT relied on qualitative and quantitative methods, further empirical testing is required to validate its real-world effectiveness. Pilot projects and case studies should be conducted to assess the framework's impact on animal traceability, disease control, food safety, and economic outcomes. These initiatives would provide valuable insights for iterative improvements, enabling the framework to maximize its potential and scalability. By linking these limitations to targeted research efforts, the study lays a clear foundation for advancing animal traceability systems in Botswana and beyond.

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Agris on-line Papers in Economics and Informatics

Volume XVII Number 1, 2025

The Influence of Climate Information Services on Climate-Smart Agricultural Investment Decisions among Smallholder Maize Farmers in Northern Ghana

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Abstract

Climate change poses significant threats to agricultural productivity in Africa particularly in regions that are dependent on rainfed agriculture. Despite the critical role of climate Information Services (CIS) in promoting adaptive practices, there is limited understanding of their impact on investment in Climate-Smart Agriculture (CSA). This study addresses this knowledge gap by examining how different sources of CIS influence smallholder maize farmers' decisions to invest in CSA practices. Using a cross-sectional survey of 566 maize-producing households across five districts in Northern Ghana, we employ descriptive statistics, the Principal Component Analysis (PCA), and a binary logit model to identify key determinants of CSA investment. The findings revealed that frequent access to daily and seasonal weather forecasts, as well as indigenous weather predictions significantly influences farmers' willingness to invest in CSA practices. Critical factors driving these decisions include maize farm size, level of commercialisation, gender, farm income and extension service visits. The results demonstrate that improving the accuracy and accessibility of CIS through traditional media, mobile platforms, and community engagement can significantly enhance investment in CSA. The key policy recommendations include promoting gender inclusivity, integrating indigenous knowledge with scientific forecasts, and expanding access to financial and advisory support. These are critical for promoting resilience and sustainability among maize-producing households in northern Ghana.

Keywords

Climate information, climate-smart agricultural practices, farm-level decisions, CSA investment, Northern Ghana.

Shaibu, A.-F., Anaman, K. A., Osei-Asare, Y. B. and Adaku, A. A. (2025) "The Influence of Climate Information Services on Climate-Smart Agricultural Investment Decisions among Smallholder Maize Farmers in Northern Ghana", *AGRIS on-line Papers in Economics and Informatics*, Vol. 17, No. 1, pp. 113-132. ISSN 1804-1930. DOI 10.7160/aol.2025.170109.

Introduction

Climate change, characterized by extreme weather conditions and variable precipitation patterns, is significantly reducing crop yields and agricultural productivity, making it increasingly difficult for farmers to maintain their livelihoods. The adverse effects of climate change include changes in temperature, precipitation patterns, and an increased frequency of extreme weather events such as floods and droughts. These changes pose a substantial threat to agricultural systems, particularly in Africa that rely heavily on rainfed agriculture (Serdeczny et al., 2017; Kang et al., 2009; Ahmad et al., 2020; Zeppel et al., 2014).

Africa's agricultural sector is especially vulnerable to climate change due to its dependence on natural rainfall and limited capacity for adaptation. Rainfed agriculture, which predominates in many parts of Africa, is highly sensitive to changes in precipitation and temperature. In regions like the Sahel and North-East Africa, characterised by semi-arid conditions and highly unpredictable rainfall patterns, communities frequently face extreme climate challenges, including droughts and devasting floods (Haile, 2005; Naz and Saleem, 2024). Variability in rainfall can lead to water scarcity during critical growing periods or waterlogging and soil erosion during excessive rainfall events, both of which negatively impact crop yields and food security (Serdeczny et al., 2017). Additionally, temperature increases can increase crop maturation and reduce the growing period, leading to lower yields, which can compromise food quality (Kang et al., 2009).

As a response to these challenges, Climate-Smart Agriculture (CSA) has emerged as a strategic approach designed to enhance agricultural resilience. It aims to achieve three main objectives: sustainably increasing agricultural productivity and incomes, adapting and building resilience to climate change, and reducing or removing greenhouse gas emissions wherever possible. These goals are essential for supporting national food security and development in the context of climate change (Adedeji, 2014; FAO, 2013; Lipper et al., 2014; Sarker et al., 2019).

Central to the success of CSA is the role of Climate Information Services (CIS). CIS provide timely and relevant climate-related data, forecasts, and analyses that are crucial for farmers and decision-makers. These services include weather forecasts, seasonal climate predictions, and historical climate data, which are disseminated through various channels such as radio, mobile phones, and extension services. By accessing accurate and up-to-date climate information, farmers can make informed decisions regarding crop selection, planting dates, and other important agronomic management practices, thereby reducing the risks associated with climate variability (WMO, 2018; Elazegui et al., 2017).

CIS empower agricultural stakeholders, particularly smallholder farmers, to make decisions that mitigate the impacts of climate variability and change. For instance, timely weather forecasts can help farmers optimize irrigation schedules, apply fertilizers more effectively, and take preventive measures against pests and diseases. Seasonal forecasts allow for strategic planning, such as diversifying crops or changing cropping patterns to suit anticipated climatic conditions. By integrating CIS into their decision-making processes, farmers can enhance their adaptive capacity and resilience to climate change (Elazegui et al., 2017).

Despite the recognized importance of CIS, there is a gap in understanding its impact on farmers' willingness to invest in CSA practices, particularly in Northern Ghana which is characterized by agro-ecological diversity and vulnerability to climate change (Damba et al., 2021). The region's reliance on maize farming and the varying access to climate information among farmers make it an ideal case for exploring how CIS influences agricultural investment decisions.

This study aims to fill this gap by analysing the influence of CIS on investment decisions in CSA among maize-producing households by examining how different sources and types of climate information affect farmers' investment choices. The research seeks to provide insights that can support sustainable agricultural development in the region. The findings are expected to provide recommendations that enhance the dissemination and utilization of CIS to promote investment in Climate Smart-Agriculture and improve the resilience of farming communities in Northern Ghana

Overall, this study adds to the literature by providing empirical evidence on the relationship between CIS and CSA investment decisions, offering context-specific insights for Northern Ghana, and promoting both theoretical understanding and practical applications in sustainable agriculture and climate adaptation.

Literature review

Climate Information Service (CIS) play an important role in assisting smallholder farmers in climate-smart agricultural advocacy and assisting farmers in making informed decisions related to agricultural practices. They provide farmers with critical information regarding weather patterns, forecasts and other agricultural advisory services. Farmers gain valuable knowledge that enables them to adjust their farming practices in response to changing climatic conditions by leveraging CIS, to enhance their adaptability and resilience.

Various studies have underscored the profound impact of CIS on agricultural decision-making processes among smallholder farmers. For example, through access to timely and accurate climate information, farmers are better equipped to anticipate and mitigate potential risks associated with climate variability and change (Baffour-Ata et al., 2022). Studies by Born, (2021) and Partey et al., (2018) suggest that CIS empower these farmers to implement appropriate strategies such as adjusting planting schedules, selecting appropriate crop varieties, adopting water-harvesting techniques, or implementing soil conservation measures. By integrating climate information into their decision-making processes, farmers can optimize productivity while minimising unhealthy environmental impacts. Overall, the utilization of CIS represents a significant advancement in supporting smallholder farmers' ability to cope with climate uncertainties and build resilience in their agricultural systems.

In Ghana, climate information facilitates agricultural decisions across different modes of production. However, the degree of impact and the specific decisions affected vary based on the scale of farming operations: For subsistence farming, farmers rely heavily on accurate information on the onset and cessation of rains in determining the best times for planting and harvesting (Antwi-Agyei et al., 2021), crop selection, soil and water management techniques. (Antwi-Agyei et al., 2012). For smallholder farmers, accurate climate information can help in integrated pest management, financial decisions and crop diversification. For commercial farmers the most important considerations in the use of accurate climate data are long-term forecasts, technology integration such as irrigation, precision agriculture, supply chain management and sustainable practices (Baffour-Ata et al., 2022; Yaro, 2013). These studies highlight three main cross-cutting issues, namely; capacity building through training and education of farmers across all levels about the interpretation and use of climate information to enhance their ability to make informed decisions. Secondly, there is a need to promote access to information through the appropriate dissemination channels such as radio, mobile technology, and extension services to provide timely and accurate climate information to farmers. The third and final issue is government-supportive programmes to enhance access and adaptive practices.

Numerous studies have also examined the factors that influence the effective utilization of climate information services by smallholder farmers. Vaughan et al. (2019) identified factors such as trust in the information source, perceived relevance, and ease of understanding as critical determinants of CIS uptake among farmers in Senegal. Similarly, Nyadzi et al. (2019) highlighted the importance of integrating indigenous knowledge with scientific climate information to enhance the relevance and usability of CIS for smallholder farmers in Northern Ghana. However, despite the growing body of research on climate information services and agricultural decision-making, there is a need for context-specific studies to understand the unique challenges and opportunities faced by smallholder farmers in different regions. In the context of Northern Ghana, where maize production is a significant economic activity and a staple crop (Adu et al., 2014), understanding the influence of CIS on investment decisions related to climate-smart agricultural practices is crucial for promoting sustainable and resilient farming systems. This study aims to contribute to the existing literature by providing insights into the utilization of climate information services and their impact on investment in CSA among maize farmers in Northern Ghana.

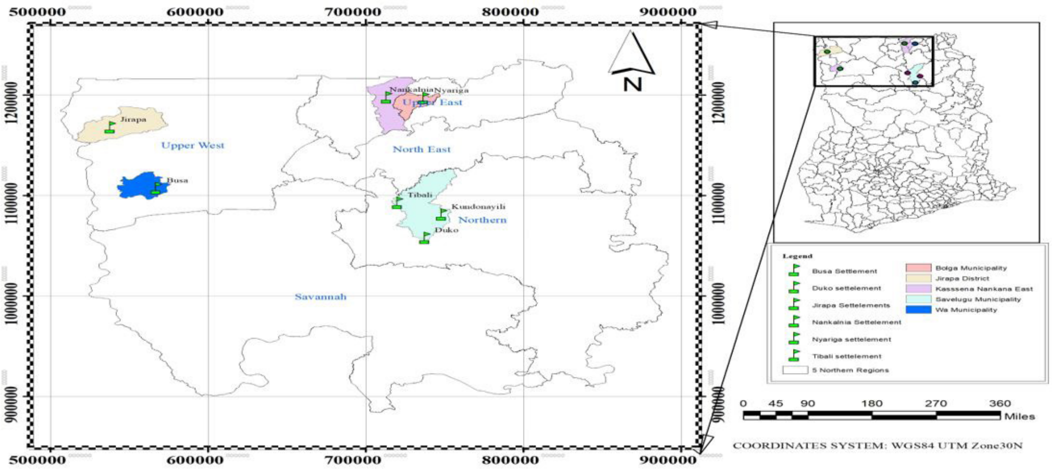
By assessing the extent to which access to climate information facilitates farm-level decisions related to land preparation, planting, harvesting, and marketing, the research will shed light on the role of CIS in supporting climate-informed agricultural practices. Additionally, by evaluating how climate information influences farmers' investment decisions in agricultural inputs and other climate-smart practices, the study will contribute to the development of strategies and policies to enhance climate resilience, productivity, and food security in Northern Ghana.

A study by Shahbaz et al., (2022) indicates that adaptation of Climate-smrt agricultural (CSA) methods is critical as climate change threatens the viability of farms run by women in Pakistan. The limited resources, cultural norms, and lack of decision-making authority faced by Pakistani women farmers hinder their ability to adjust to climate change. Women farmers with higher decisional empowerment and innovativeness positively influence the adoption of CSA practices across all resource groups, increasing adoption by 0.54 compared to low empowerment levels (Shahbaz et al., 2022). The study provides useful information, but one potential flaw is that it doesn't look at how male and female farm household members' joint decision-making influences CSA adoption.

Materials and methods

The study area

This study was carried out in the Northern, Upper East and Upper West regions of Ghana covering 5 districts and 7 communities which are identified as climate-smart villages by ongoing CSA projects involving 566 maize-producing households (Figure 1). The climatic conditions in these regions are defined by a single rainy season from May to October, with a peak in August and September, followed by an extended dry period from November to April (Bessah et al., 2022). The annual rainfall is generally low, ranging from around 800 mm to 1,100 mm, decreasing from north to south.



Source: Town and Country Planning, 2023

Figure 1: Map showing the study area.

Temperatures are consistently high throughout the year, with mean annual temperatures ranging from 27°C to 36°C, and the hottest months being March and April (Ampadu et al., 2019; Atiah et al., 2021).

The vegetation is predominantly savannah grasslands and drought-resistant, reflecting the semi-arid climate (Atiah et al., 2019). The single rainy season allows for one major growing season for crops such as millet, sorghum, maize, and groundnuts. However, irrigation is necessary for year-round agriculture due to the extended dry season. Water scarcity during the long dry season is a significant challenge in these regions, particularly in the Upper East region (Ampadu et al., 2019b). Furthermore, the study area is prone to drought conditions (Adonadaga et al., 2022), which can have severe impacts on agriculture and food security. Occasional flooding also occurs during the rainy season, especially in low-lying areas (Owusu et al., 2016).

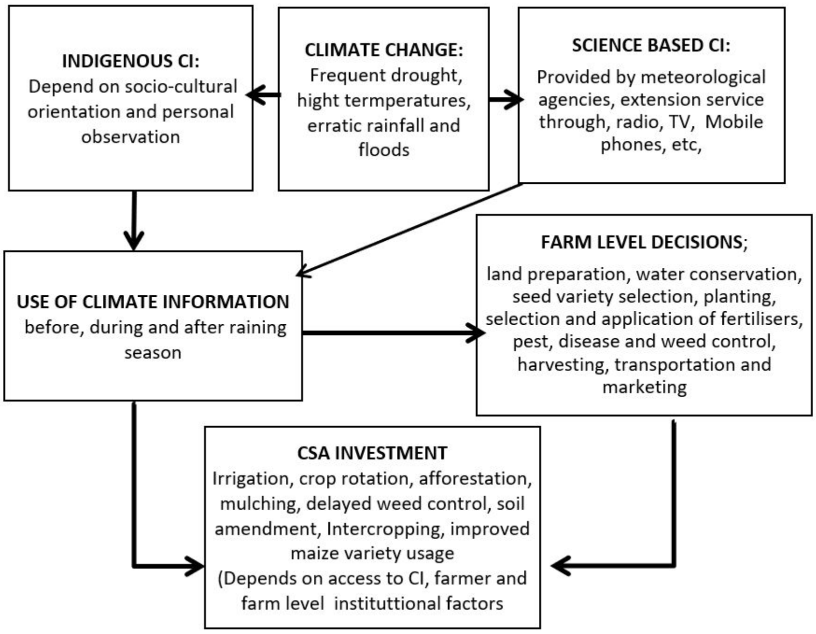
The selection of study communities was based on their climatic vulnerability and relevance to maize farming. The specific locations were chosen to capture a diverse range of farming conditions and access to CIS.

Conceptual framework

Climate change is a complex phenomenon characterized by stronger winds, hotter temperatures, more frequent droughts, unpredictable rainfall, and increased flooding. In the context of Northern Ghana, access to and utilization of climate information services are influenced by individuals' perceptions of climate change (Partey et al., 2020). Climate services play a crucial role in empowering farmers to make informed decisions regarding climate-smart agricultural (CSA) investments at the farm level, with the potential to enhance output, income, and food security (Born, 2021).

The conceptual framework (Figure 2) proposes two interconnected pathways through which access to climate information services influences farmers' CSA investment decisions. The first pathway involves the collection and analysis of scientific agro-climate data obtained from meteorological services using information and communication technology (ICT) platforms such as radio, TV, and mobile phones, as well as indigenous climate knowledge which relies upon experiences from socio-cultural perspectives and personal observation. By leveraging these resources, farmers gain a deeper understanding of climate patterns and are better equipped to make farm-level decisions regarding land preparation, water conservation, seed variety selection, planting, selection and application of fertilisers, pest, disease, weed control, harvesting, transportation, and marketing.

The second pathway emphasizes the use of these climate variables which covers periods before, during, and after each rainy season for CSA investment decisions. By strengthening these linkages and supporting initiatives aimed at promoting climate resilience, the risks associated with agriculture can be reduced (Born, 2021). Overall, the conceptual framework highlights the significance of access to climate information for smallholder farmers in the face of climate



Source: Authors' elaboration from literature

Figure 2: Conceptual framework of the study.

change. By integrating climate services into their decision-making processes, farmers in Northern Ghana can make informed choices regarding CSA investments, thereby enhancing their adaptive capacity and mitigating the adverse effects of climate change.

Sampling and data collection and procedures

We employed a multi-stage stratified random sampling technique to select 566 maize-producing households, ensuring representative coverage across different agricultural regions. The first stage involved a purposive selection of five districts from the Northern, Upper East, and Upper West regions, where CSA villages were identified. The selected districts are Savelugu Municipality in the Northern Region, Bolga Municipality and Kassena Nankana District in the Upper East, Wa Municipality and Jirapa District in the Upper West Regions. In the second stage, Seven CSA communities were randomly selected from a population of ten in the five districts. The selected communities are Tibali, Duko and Kundoonayili (Savelugu Municipality), Nyariga (Bolgatanga Municipality), Nankalnia (Kassena Nankana District,), Busa (Wa Municipality) and Jirapa (Jirapa District). In the third and final stage, 566 maize farm households were randomly selected from a population of cereal crop households obtained from Ghana's Ministry of Food and Agriculture (MoFA) Facts and Figures for 2020. The sample size was determined based on the following assumptions:

1. A 95 percent confidence interval. This was to ensure that the right decisions were made about the sample for the study (Taherdoost, 2017).
2. A 5 percent level of significance. This means the probability of rejecting the null hypothesis when it is true or when it should be accepted is about 5 percent or less.
3. Since we do not have control over the research participants a 90 percent response rate was assumed.
4. The objective of the sample size determination was to look for some cases that would yield the smallest effect for the test conducted with the survey.
5. Maize-producing households were assumed to be identifiable.

To obtain the sampling frame for the three study regions, the study used the Ghana Agricultural Census data for 2018, which was obtained from MoFA (2020). Based on administrative regions and districts, the study calculated an appropriate sample of 1,113 smallholder cereal staple farmers. However, due to time and resource constraints, only 50% of the estimated sample was used for the study resulting in 566 cases chosen at random from the study regions. Some studies including Bujang et al., (2018) Burgess et al., (2016), and Taherdoost, (2016) have recognised the real-world limitations of time, money, and resources, which may force the use of smaller sample sizes than anticipated or ideal. The significance threshold was set at 0.05%, with a 95% confidence level, using the Yamane (1973) formula denoted in Equation 1:

$$n = \frac{N}{1 + N(\propto^2)} \quad (1)$$

Where; n is the sample size, N is the population or sample frame (total number of cereal crop households), and $\propto$ is the level of precision. The ideal samples for the Northern Upper East and Upper West regions of Ghana were computed by substituting N with the values obtained from MoFA Facts and Figures for 2018 (MoFA, 2021), the Ghana Agricultural census report for 2018 and the Ghana 2021 Population and Housing Census (Ghana Statistical Service, 2021, 2020). In Table 1, the specifics of the sample size determination are shown.

The study relied heavily on original data gathered through a survey. Data were collected mainly through structured questionnaires. We conducted a thorough pre-testing and validation procedure for the questionnaire to guarantee the validity and reliability of our research tool. For pre-testing, we chose 90 households in total, 30 from each of the three regions (Northern, Upper East, and Upper West). Despite not being included in the final sample, these households had traits in common with our target group. In the pre-testing, pilot interviews were conducted with selected households, observing their interpretation and answering questions. Feedback was sought on clarity, relevance, and difficulties encountered. Questionnaires were analyzed for inconsistencies and potential issues and revised accordingly.

To validate the questionnaire, we used multiple methods. First, we checked the replies for content validity by cross-referencing them with previously published studies and expert opinions. Second, we ran factor analysis on the data to make sure the constructs were legitimate. We also checked the replies for criterion validity by cross-referencing them with publicly accessible information, like official Ministry of Food and Agriculture agricultural yield records. We calculated Cronbach's alpha for each relevant question set to make sure they consistently measured the same concept and to ensure internal consistency, a subset of twenty households from the pre-test sample were re-interviewed after a two-week gap to ensure response consistency to assess test-retest reliability.

The survey period spanned August 2023 to December 2023, ensuring data collection covered both the peak growing season and the post-harvest period, allowing a comprehensive understanding of farming decisions influenced by CIS.

Analytical methods

Descriptive statistics and Principal Component Analysis (PCA) were employed to assess various CIS sources and variables considered by farmers in decision-making. A binary logit model was used to explore factors influencing farmers' willingness to invest in CSA practices. To examine the use of scientific and indigenous climate information in farm-level decision-making among maize farm households, a combination of descriptive and inferential analytical techniques was applied.

Region/Dist.	Community Name	Cereal Staple HH	Study District HH	Estimated sample	Selected Sample
Northern		86,732	4,336	366	**186**
Savelugu	Tibali				62
	Kundonayili				62
	Duko				62
Upper East		54,936	6,043[1]	375	**191**
Bolga	Nyariga				95
Kassena N	Nankalkania				96
Upper West		28,675	5,162[2]	371	189
Wa	Busa				89
Jirapa	Bompari/Jirapa				100
TOTAL				**1,112**	**566**

Note: [1] Average HH for Bolga and Kassena Nankana, [2] Average HH for Wa and Jirapa
Source: Authors' elaboration from MoFA (2021) and GSS (2021 and 2020)

Table 1: Sampling frame and sampling size determination.

Specifically, the study investigated the use of climatic information in farm-level decision-making using the Principal Component Analysis. Input variables such as the onset of rain, precipitation, temperature, wind direction/speed, sunshine, and humidity were used, while output variables such as land preparation, water conservation, seed variety selection, planting schedules, fertilizer application, pest and disease control, weed control, and harvesting were used.

The ability to get detailed insights into the elements that increase the chance that a person will be aware of, have access to, and utilize a particular climate information service is one of the main advantages of employing different methods. Given that farmers engage with climate information services in a variety of ways (Botchway et al., 2016; Vedeld et al., 2019), this approach is compatible with the complex systems concept which is the main focus of this research. As a result, multiple analytical techniques are used to show the diversity of processes and factors influencing farmer access and decision-making.

Descriptive analysis of climate information access and use

To analyse climate information access and use, we used correlation matrices and contingency tables, in addition to chi-squared tests, to gain further insight into district-specific trends observed in the study using the onset of rain, precipitation, temperature, wind direction/speed, sunshine, and humidity. The study investigated the use of climatic information in farm-level decision-making, using factor analysis. We gathered data on the several farm-level decisions that farmers usually make and the climate information that they take into account. Factor analysis is a widely used technique in social science research, including studies on agriculture, to uncover the underlying constructs or factors that influence particular behaviours or decisions and to investigate intricate interactions between numerous variables. (Abacı and Demiryürek, 2019; Mellon-Bedi et al., 2020).

Three categorised climate variables namely; daily weather forecast, seasonal weather forecast and indigenous weather projections were examined concerning farm-level decisions, such as land preparation, water conservation, seed variety selection, planting schedules, fertilizer application, pest and disease control, weed control, and harvesting. Multiple analytical techniques were utilized to showcase the diversity of processes and factors that influence farmer access to climate information and decision-making at the farm level. Given that farmers engage with climate service products in various ways, employing different methods aligns with the complex systems concept.

The Determinants of Households' Willingness to Invest in CSA Practices

The drivers of maize farmers' household annual willingness to invest (WTI) in climate-smart agricultural practices were estimated using the binary logit model. WTI is conceptualized as the amount deducted from a farmer's revenue while maintaining the utility of their consumption of CSA practices. As an alternative, it is the highest amount a farmer is willing to invest in CSA to maintain utility or benefits in terms of yield and income in the face of climate variability.

Following the work of (Abugri et al., 2017) the WTI may be stated generally as a utility function:

$$V(y - WTI,_{p,q1} : Z) = V(_{y,p,q0} : Z) \quad (2)$$

Where *WTI* is the willingness of maize-producing households to invest in CSA, y is the farmer's income, V stands for the indirect utility function, q_0 and q_1 are the quality levels of CSA in terms of yield, or net return with $q_1 > q_0$ indicating that q_1 gives improved yield from a CSA practice. p is a vector reflecting the price or cost of CSA practices incurred by farm households. Individual households' socioeconomic characteristics and institutional variables are represented by Z. Using maximum bids for each CSA practice, the mean amount of *WTI* is calculated as a continuous variable from open-ended response values. The following equation was used to statistically estimate the mean *WTI* using the average of the lowest and highest bids given by the respondents;

$$meWTI = \frac{1}{n}\sum_{i=1}^{n} yi \quad (3)$$

Where *meWTI* is the mean willingness to invest in CSA practice, n is the sample size and *yi* is the reported average bid for each CSA. The farmer or farm-level characteristics and institutional elements that are likely to influence their decisions to invest (pay a minimal price) in CSA practice to improve maize yield and net returns must be identified after assessing farm household *WTI*. Such farmer/farm-level characteristics may be modelled using the binary logit model or binary probit (Daberkow and McBride, 2003; Letaa et al., 2015).

At any given time, a complex combination of socioeconomic, demographic, institutional, and biophysical factors affect farmers' decisions to adopt or reject new technologies. Therefore, it has become crucial to model farmers' reactions to agricultural innovation practices from a theoretical and empirical perspective. A mixture of qualitative and quantitative data may be used to analyse the link between adoption and its determinants. This type of study uses a binary dependent variable, where a value of 1 denotes the presence of an event and a value of 0 denotes its absence. Qualitative response models must be used for analysing such connections.

Within this context, linear probability models (LPM) are one potential strategy. A linear function of the explanatory variables is how the binary dependent variable is expressed in LPM. Although it is technically possible to estimate LPM using the conventional Ordinary Least Squares (OLS) method as a simple operation, this method has some drawbacks (Alabi et al., 2020). when using OLS regression with a binary dependent variable the results show heteroscedastic error structure and inefficient parameter estimations. As a result, confidence interval creation and hypothesis testing become unreliable and possibly deceptive (Achen, 2021; Das, 2019). Furthermore, a linear probability model might forecast values outside of the 0–1 range, which would be against the basic rules of probability. The logit and probit models are often used as qualitative response models to handle these issues and generate significant empirical results (Gujarati, 2022).

Because logit and probit models share many statistical similarities, choosing between them might be difficult. Nevertheless, within the middle range, the logistic and cumulative normal functions are very similar to one another (Stank et al., 2017). The primary distinction between the logistic and probit formulations lies in the fact that the logistic model exhibits slightly thicker tails, meaning that the logistic curve approaches the axes more slowly compared to the normal curve (Gujarati, 2022). As a result of these elements, the logistic distribution function, often known as the logit model, was selected because it closely resembles the cumulative normal distribution. Besides, it provides simplicity from a mathematical standpoint and permits a useful interpretation.

Empirical model

Following the work of Gujarati (2022), the empirical logit model is expressed as follows:

$$\text{Logit}\,(P\,(Y = 1)) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon \tag{4}$$

Where P (Y=1) represents the probability that a maize-producing household is willing to invest in Climate agricultural practices. Logit (P (Y=1)) is the log odds of a maize-producing household being willing to invest, $\beta_0 \ldots \beta_n$ are the parameter estimates for the independent variables, $X_1 \ldots X_n$ the independent socioeconomic and institutional variables such as age, education, distance to the nearest market, access to climate information, and farm size; ε represents the error term.

Results and discussion

Key findings

The results indicate that the most utilized Climate Information sources among farmers were daily weather forecasts, followed by seasonal forecasts and indigenous knowledge. Additionally, farmers who frequently used CIS were more likely to invest in CSA practices, highlighting the importance of timely and accurate climate information. However, it must be noted that the variation in N in Figures 3 and 5 does not imply negligence but rather highlights the context-specific priorities and constraints of smallholder farmers. It demonstrates that farmers prioritise climate information based on its relevance to their specific farming activities and challenges, accessibility through various channels such as radio, TV, mobile phone, extension services and the ease of interpreting the data also play significant roles in determining which variables farmers actively monitor. These findings underscore the need for tailored dissemination strategies to ensure farmers can access and use relevant climate information effectively

Access to climate information

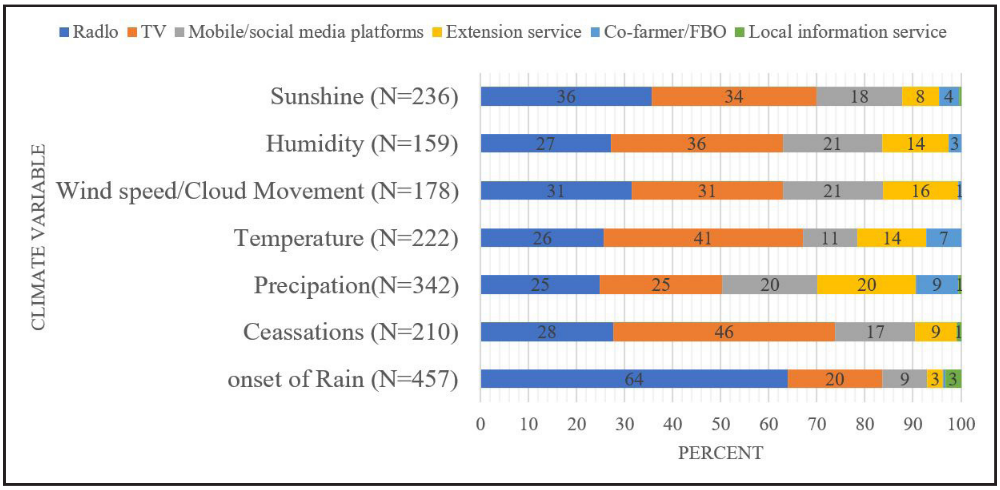
The study assesses meteorological climatic data, focusing on the sources, format, and usefulness of the information received from these sources. It also examines the indigenous climatic knowledge, evaluating the likelihood of seven different indigenous climatic indicators occurring when farmers notice these signals (Figure 3).

The study analysed the primary sources of weather and climate information across various meteorological parameters, revealing a consistent respondents' reliance on diverse media channels for dissemination of climate information.

For sunshine information, radio emerged as the leading source, accounting for 36 % of reports, followed closely by TV. In the case of humidity, TV was the dominant source at 36%, followed by radio. Wind speed and cloud movement data were evenly distributed between radio and TV, each providing 31% of the information while mobile/social media platforms contributed 21%. For temperature information TV again is the dominant channel as the primary source of receiving climate information with 41% of responses followed by radio at 26%. Precipitation data showed that the proportion respondents reliant even reliance on both radio and TV is even, each contributing to 25% of the information while mobile/social media platforms accounted for 14%. For cessation, TV was the primary source with 46% or respondents claiming to be receiving information from these sources. Finaly for the onset of rain, radio played a dominant role providing 64% of information followed by TV with 20%.

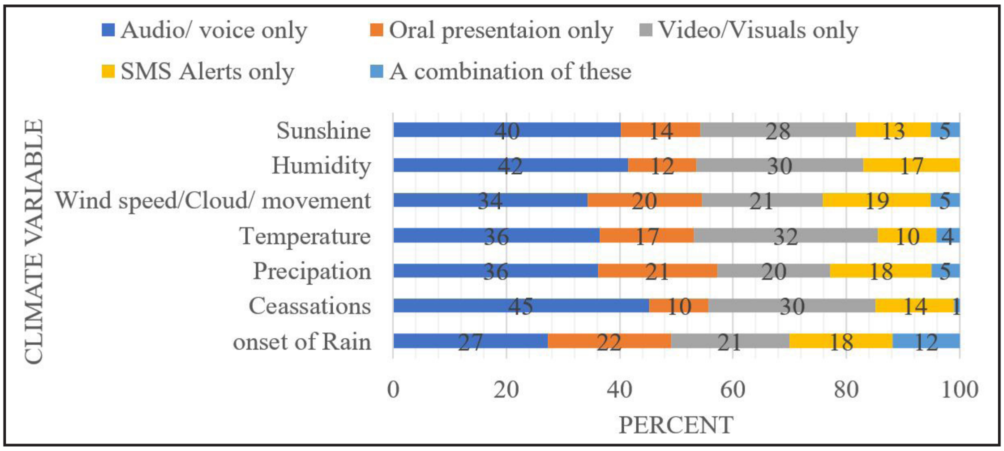
Overall, the findings suggest that radio and TV consistently serve as the most relied-upon sources of climate information across all meteorological parameters. Mobile and social media platforms, along with extension services, play secondary but significant roles as well, while information from co-farmers, Farmer-based organisations, and local information service centers have limited influence in the dissemination of weather and climate information.

The analysis of information transmission formats reveals predominant channels across various meteorological data types (Figure 4). Audio/voice consistently emerged as the primary transmission method, ranging from 27% (onset of rain) to 45% (cessations).



Source: Authors' elaboration from survey 2023

Figure 3: Main sources of climate information.



Source: Authors' elaboration from survey 2023

Figure 4: Climate information transmission.

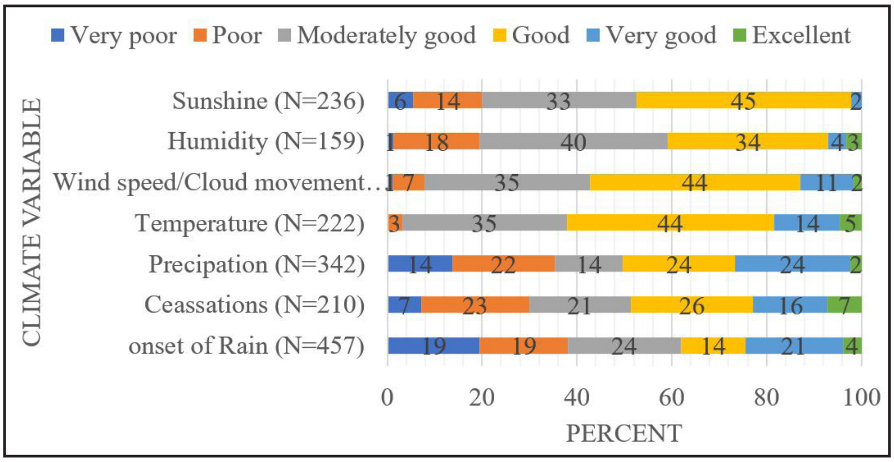
Video/visuals were the second most common channel, with percentages varying between 20% (precipitation) and 32% (temperature). Oral presentations followed, representing 10-22% of transmission methods. SMS alerts accounted for 10-19% of channels, while combined methods represented the smallest proportion, typically around 1-12% of transmissions. Each climatic information variable showed slight variations in transmission preferences, but audio/voice and video/visuals dominated across the board.

Figure 5 presents the results of the usefulness of climate information received by farmers. They were evaluated based on dependability, correctness, and general applicability using a Likert scale from 1 to 6 the following criteria to rate these variables by households (1 = very poor, 2 = poor. 3 = moderately good, 4 = good, 5 = very good, and 6 = excellent). The survey results revealed nuanced perceptions across different meteorological information types. Sunshine information received generally positive ratings, with nearly half of respondents (45%) considering it "Good" and a third (33%) rating it as "Moderately good". Humidity followed a similar pattern, with 40% rating it "Moderately good" and 34% deeming it "Good".

Wind speed and cloud movement ratings paralleled these trends, with 44% rating it "Good" and 35% selecting "Moderately good". Temperature information showed comparable results, with 44% rating it "Good" and 35% choosing "Moderately good". Precipitation data displayed more varied assessments, with equal proportions (24%) rating it "Good" and "Very good", and 22% considering it "Poor". Cessations information had a more mixed reception, with 26% rating it "Good", 23% rating it "Poor", and 21% selecting "Moderately good"

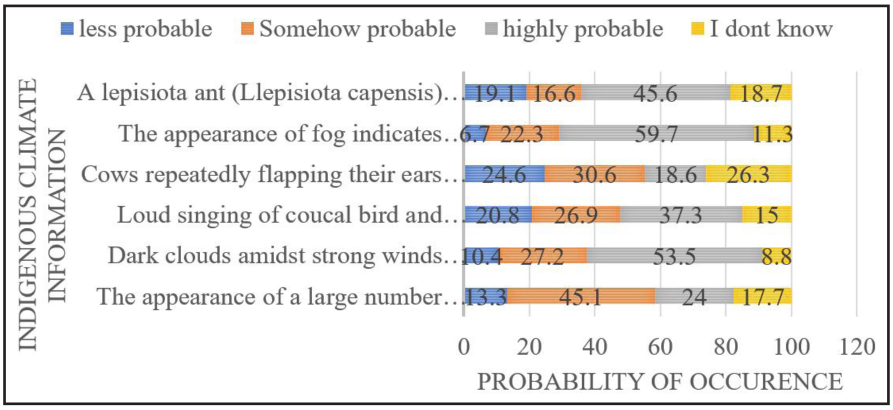
In general, most climate variables were rated positively, with "Good" and "Moderately good" being the most common ratings. Precipitation and onset of rain information demonstrated more varied usefulness ratings compared to other variables.

Assessment of the local climate knowledge in the study area is shown in Figure 6. While



Source: Authors' elaboration from survey 2023

Figure 5: Usefulness of climate information received.



Source: Authors' elaboration from survey 2023

Figure 6: Assessment of indigenous climate knowledge for all districts.

lepisiota ants move their eggs uphill during the rainy season, 45 percent of respondents said it is extremely likely that rain will fall. According to 60% of responses, the emergence of fog also indicates the impending arrival of rain. Also, according to 53% of respondents, the presence of heavy clouds and strong winds indicates a high likelihood of rainfall during the next day or a few hours. However, the majority of respondents, about 45% believe that rain can coincide with the appearance of large earthworms on a given day. Overall, any indigenous weather or climate observed slightly or strongly suggests rainfall.

Use of climate information in farm-level decisions

Factor analysis was utilized to discern the key dimensions or factors relevant to incorporating climate information into farm-level decisions. In particular, Principal Component Analysis (PCA) was applied, employing a Varimax rotation approach. This method plays a crucial role in revealing the underlying components within the data, shedding light on its structural patterns. Within the rotated component matrix, the loadings of individual variables on three extracted components are revealed.

Firstly, the Kaiser-Meyer-Olkin (KMO) and Bartlett's tests are used to determine if the data was acceptable for factor analysis. While the KMO assesses sampling adequacy and data suitability, Bartlett's test of sphericity examines the null hypothesis that the correlation matrix is an identity matrix, indicating that the variables are uncorrelated. The results of the test presented in Table 2 suggest that the data is reasonably acceptable for factor analysis, based on the KMO value of 0.649. The estimated chi-square value of 638.854 with 36 degrees of freedom and a significance level of 0.000 from Bartlett's test indicates that the null hypothesis is rejected, showing that the data is appropriate and the correlation between variables is strong enough to uncover underlying elements.

Factor 1 is characterized by substantial factor loadings associated with variables related to daily weather forecasts, with particular emphasis on "Climate information that offers immediate decisions at the farm level" (0.744), "Climate information which is precise" (0.647), and "Climate information that allows effective crop management" (0.621). This underscores the pivotal role that accurate and timely daily weather forecasts play in farm-level decision-making and the successful management of crops. Farmers utilize daily weather forecasts to optimize their agricultural practices. This information enables them to plan irrigation schedules, apply fertilizers and pesticides at optimal times, and schedule harvesting activities to coincide with favourable weather conditions (Obert et al., 2016). Additionally, forecasts help farmers anticipate and mitigate risks associated with unexpected weather events, thereby safeguarding crop yields and ensuring the sustainability of their farming operations (Klemm and McPherson, 2017).

Factor 2 has significant factor loadings for the statements "Climate information allows for long-term planning" (0.793) and "Climate information allows mitigation planning" (0.704), which are variables related to seasonal weather forecasts. This demonstrates the significance of seasonal weather forecasts for long-term agricultural planning and risk reduction. Farmers can benefit from seasonal forecasts in many ways, including crop selection, irrigation management, pest and disease control, crop rotation and land use, infrastructure investments, and preparedness for drought and floods. They support farmers with resource allocation, irrigation schedule planning, and planting and harvesting schedule adjustments. Long-term weather patterns can also be used to optimise yields, cut down on waste, and allocate resources more wisely. In addition to directing infrastructure investments in areas vulnerable to extreme weather, such as irrigation systems and climate-resilient storage facilities, long-term forecasts also aid in the creation of preparedness plans.

Factor 3 is defined by a high factor loading for the statement "CI allows for trust in local knowledge" (0.828). This finding highlights the value of local indigenous knowledge of the weather and implies that it plays a vital role in farm-level decision-making such as land preparation, fertiliser application, seed selection, weed and pest control, and harvesting. Indeed, some studies report that indigenous climate knowledge is rooted in local cultures and traditions, making it highly relevant to farmers. however, it is specific to a region's ecosystem and weather patterns, enabling farmers to make decisions tailored to their region (Ajani et al., 2013; Balehegn et al., 2019). Additionally, there is a connection between indigenous climate calendars and sustainable farming practices which lies in the seamless integration of traditional ecological knowledge into farmers' decision-making processes. For example, from the perspectives of Balehegn et al., (2019), indigenous climate information can provide insights into potential risks and uncertainties associated with weather patterns, enabling farmers to develop strategies for mitigating them. Thus, community collaboration and trust in indigenous climate information increase the likelihood of farmers relying on it for decision-making.

The results of the factor analysis indicate that the studied climatic variables can be categorized into two main constructs. Factor 1 focuses on factors providing immediate and precise information for farm-level decisions, effective crop management, and timely crop harvest. This is likely associated with daily weather forecasts from meteorological agencies and similar institutions. Factor 2, however, is centered around climate information conducive to long-term planning, mitigation against climate hazards, and water conservation, suggesting a distinct construct related to seasonal weather forecasts. Factor 3, comprising climate information that builds trust in local knowledge, is easily accessible and cost-effective, providing supplementary information related to indigenous weather predictions. In summary, the study underscores the importance of considering various climatic variables in analyzing their impact on farm-level decisions, emphasizing the relevance of daily, seasonal, and indigenous weather projections and predictions for such analyses.

Determinants of household willingness to invest in CSA

A binary logistic regression model was used to analyze the impact of socioeconomic and institutional factors on maize-producing households' decisions to invest in climate-smart agricultural practices. Eleven variables were included in this investigation, and eight of them were statistically significant at levels between 5% and 1%. Table 3 summarizes the results.

Model diagnostics

The diagnostic test in the logit model demonstrates model performance and goodness-of-fit. The degree to which the model fits the data is gauged by the log-likelihood. Maximising the likelihood function is the objective of logistic regression. The lower value for the model's deviation, of 274.424, indicates a better fit for the model. A pseudo-R-squared statistic called Cox and Snell R-squared shows how much of the variation in the dependent variable is explained by the logistic regression model. A result of 0.465 indicates that 46.5% of the variation in the dependent variable is explained by the model. Unlike R-squared in linear regression, it doesn't have a clear explanation,

Items/Factor/Climate information	Mean	Factor loadings	Percentage of variance explained
Factor 1: Daily Weather Forecast	Â	Â	16.1
CI offers immediate decisions at the farm level	1.3834	0.744	
CI is precise	2.136	0.647	
CI allows effective crop management	2.0848	0.621	
CI allows for a timely harvest	2.5512	0.421	
CI required for pest and disease control	2.765	0.114	
Factor 2: Seasonal Weather Forecast	Â	Â	13.96
CI allows for long-term planning	1.7756	0.793	
CI allows mitigation planning	2.6678	0.704	
CI allows for water conservation plans	2.2544	0.49	
Factor 3; Indigenous Weather predictions	Â	Â	12.89
CI allows for trust in local knowledge	2.636	0.828	
CI is easily accessible and less costly	2.6078	0.21	
CI provides supplementary information	2.4806	0.208	
KMO Measure of Sampling Adequacy			0.649
Bartlett's Test of Sphericity	Approx. Chi-Square		638.854
	df		36
	Sign		0

Source: Authors' elaboration from survey 2023

Table 2: Principal Component Analysis (Varima Rotation Method).

although it does give some indication of the model's goodness of fit. Therefore, it should be considered a rough indicator of the goodness of fit or evaluated with other models. Another pseudo-R-squared metric is the Nagelkerke R-squared, which is a modified version of the Cox & Snell R-squared. It is 0.694, meaning that 69.4% of the variation in the dependent variable is explained by independent variables. The performance of the logistic regression model is assessed by comparing it to a null model, which has no predictors. The logistic regression model surpasses the null model in this comparison, according to the chi-square statistic, which produces a significant result of 354.333 with a p-value of 0.000 and 1 degree of freedom. Thus, a strong indication of the explanatory power of the model.

Sex of respondents

The categorical variable used to quantify sex is gender (1=Male, 0=Female). The "sex" variable's coefficient is 2.100. For a one-unit change in the "sex" variable, while holding all other factors constant, this indicates the log-odds change in the probability that farmers will spend money on climate-smart farming practices. A positive coefficient suggests that being classified as "Male" is thought to be connected with a greater log-odds of farmers' readiness to invest than being classified as "female" When all other factors are held constant the "sex" variable has a statistically significant impact on farmers' desire to invest in climate-smart farming practices at 1 percent. For example, women may have less access to credit or land, making it harder for them to invest in these practices. However, in the decision-making process for land use, Glemarec (2017b) revealed apparent inequalities in gendered knowledge, preferences, risk-taking, and access to innovation that affect t the adoption of agroforestry techniques and other investment possibilities by men and women which reflects different exposure to and perceptions of risk. This is the case in northern where women do not play leading roles in household decisions due to socio-cultural and economic factors. For example, there are still differences in how much each gender contributes to cultivation choices and how they spend their agricultural income in Northern Ghana (Yokying & Lambrecht, 2020). Nonetheless, CSA investment risks are more likely to affect female farmers than male farmers (Glemarec, 2017).

Age of respondents

The "Age" variable, which is expressed in years, has a statistically significant influence on farmers' desire to invest in climate-smart agricultural practices, with a statistical significance l evel of 1 percent. Holding other factors constant, the positive coefficient (0.158) and the corresponding odds ratio (1.171) indicate that an increase in age is linked to a greater likelihood of desire to invest in climate-smart agriculture practices. In contrast to younger farmers, elderly farmers are more likely to be prepared to invest in such practices in practical terms. This finding is in line with several previous research, such as Jahan et al., (2022;) and Ojo et al., (2021). found that farmers' age may affect their capacity to access financial resources since older farmers may have more established credit and financial stability, which may alter investment choices Investment choices can also be influenced by government initiatives and incentives aimed at particular farmer age groups. However, other research suggests that older farmers may be less risk-averse, leading them to make conservative investment decisions (Hannus & Sauer, 2020; He et al., 2019) while others may make decisions that are in line with their retirement plans, such as investments meant to provide income in retirement, (Kirkpatrick, 2016; May et al., 2019) which could lead to less investment in CSA practices.

Farm size

The "Farm Size" variable, which is measured in hectors, has a statistically significant influence on farmers' willingness to invest in climate-smart agricultural practices with a p-value = 0.001). Holding other variables constant, the positive coefficient (0.717) and the corresponding odds ratio (2.047) indicate that larger farm size is related to a higher probability of maize-producing households' willingness to invest in CSA practices. Is reported that larger-scale farmers are more inclined to implement new technologies, invest more time and resources in learning about farming techniques, and place greater emphasis on using productive rather than processing technology (Hu et al., 2022).

The evidence suggests that larger farms may have greater financial resources and access to credit, which can make it easier to invest in new technologies and practices that promote climate resilience (Idrisa et al., 2012; Lalou et al., 2019) Additionally, larger farms may have more diversified production systems and greater market opportunities, which can provide incentives for investing in climate-smart practices that improve productivity (Pascual et al., 2017). This finding suggests that opportunities for specialised interventions and capacity-building initiatives are presented by the larger farm owners' willingness to invest in CSA practices in Northern Ghana. These interventions must be created to take into account the particular requirements of farms of various sizes, fostering inclusive and sustainable agricultural growth in these regions.

Years of earming experience

This is a continuous variable measured as the number of years a farmer has spent in farming activities. Years of farming experience" is a statistically significant predictor, and it is estimated that for every additional year of farming experience, the likelihood of being willing to invest in climate-smart agricultural practices decreases by a factor of about 0.900, assuming that all other variables in the model remain constant. This implies that more seasoned farmers are more unlikely to be prepared to invest in climate-smart farming.

The association between farmers' experience and their readiness to invest in cutting-edge agricultural technology that is adaptable to climate change has been studied in some developing nations. While some studies observed positive correlations between these elements some others have reported negative correlations It has been shown, for example, that in Nigeria, farmers with a lot of experience are frequently more inclined to make irrigation infrastructure investments and choose drought-resistant crop varieties in areas prone to drought (Igberi et al., 2022). Also in South Africa, seasoned farmers could be more inclined to spend money on precision farming tools like GPS-guided tractors and sensors since they are aware of the potential advantages in terms of making the best use of resources, using less inputs, and adjusting to changing weather conditions. These stem from their familiarity with local weather and farming conditions.

On the other hand, the ability or inclination of a farmer to invest in resilient farming techniques can often be negatively impacted by their wealth of expertise, even if farming experience normally helps farmers make better decisions. Such circumstances are context-specific and, hence should not be applied in all situations. For example, farmers with a lot of experience could be quite committed to conventional farming practices (Krzywoszynska, 2019; Vitari & Whittingham, 2018). They may be accustomed to their current farming practices and may perceive new methods as unnecessary or too costly. The relationship between traditional farming practices and technology adoption is complex and content-specific but there is some evidence to suggest traditional farmers may be less likely to invest in new agricultural technology. For example, in India, farmers who had more experience with modern agricultural practices were more likely to adopt new technologies, while those who relied heavily on traditional practices were less likely to do so (Jain, 2017). This is still a problem, even in some European countries, because local farmers still place a high value on their experience, which is not being utilized to its full potential as countries move towards more sustainably-friendly agronomic practices (Šūmane et al., 2018).

Extension visits

This variable is measured as the number of extension visits received by the farmer in each farming season. The variable is statistically significant at 1 percent and it is estimated that for every additional visit of extension officers to farmers, the likelihood of being willing to invest in climate-smart agricultural practices increases by a factor of about 2.169, assuming that all other variables in the model remain constant. This implies that farmers who receive more extension visits in a season are more likely to invest in climate-smart farming. The adoption of soil conservation techniques, which are crucial for CSA, by farmers in Uganda increased dramatically as a result of increased access to extension services (Turyasingura & Chavula, 2022). According to a report by Khalid and Sherzad (2019), effective extension services offer individualized advice based on regional circumstances, which can increase the applicability of CSA techniques. Farmers are more willing to invest in techniques that are suited to their particular needs when they receive tailored guidance (Khalid and Sherzad, 2019).

Distance to the nearest market

This is a continuous variable measured in kilometres. The negative coefficient shows that a lower desire to invest in CSA practices is correlated with a longer distance of the farmer to the market. The probability of being willing to invest in climate-smart agricultural practices decreases by a factor of approximately 1.298 as the distance to the nearest market increases when all other variables in the model remain constant. The variable is statistically significant at 1%. The market here could be a maize output market or a market for CSA inputs. Farmers who are near a market may have easier access and a larger consumer base, which might result in a greater rate of turnover than farmers who must travel far to reach the market and incur related transportation expenses whether in the input or the output market.

There is a growing body of empirical evidence that suggests that distance to input and output markets is an important factor influencing farmers' decisions to invest in agricultural technologies. Such evidence is even popular among developing countries (Gollin et al., 2014; Suri and Udry, 2022). For example, in Kenya, Malawi Tanzania and some other African countries, farmers who lived closer to markets were more likely to adopt hybrid maize varieties while those who were closer to inputs markets such as improved seeds, fertilisers and other agricultural inputs were positively associated with adoption of improved agricultural technologies (Arslan et al., 2017; Fisher et al., 2015; Makate et al., 2023). According to Altieri et al., (2015), farmers in remote areas may have less access to information regarding climate-resilient farming practices and strategies and may be less exposed to agricultural innovations. This knowledge gap may have an impact on their awareness and investment inclination.

Overall, the evidence suggests that access to input and output markets is an important factor influencing farmers' decisions to invest in agricultural technologies. Therefore increased investment in new technology and improved agricultural production may result from expanding market access through policies and actions that lower transportation costs, enhance market information systems, and construct infrastructure. For farmers in Northern Ghana, where inadequate infrastructure already prevents them from accessing markets, this is essential.

Level of maize commercialisation

The variable "whether farming is mainly commercial" is treated as a binary predictor variable, and is typically coded between 0 and 1. If farming is mostly commercial, it takes on a value of 1, and 0 otherwise. The likelihood of being willing to invest in climate-smart agricultural practices is approximately 1.536 times higher when farming is primarily commercial as compared to when it is not. This predictor is statistically significant at the 5 percent significance level. Maize commercialisation and CSA investment have a complicated relationship. Some commercialization may emphasize immediate profits over long-term sustainability, which could result in resource misuse or a disregard for conservation measures. Additionally, the effects of commercialization can differ between various farming techniques and geographical areas. According to some studies such as Abdoulaye et al., (2011) and Martey et al., (2020b), higher commercialization of maize production may give farmers extra revenue they can use to finance CSA techniques. Farmers that earn greater revenue might be able to pay the initial costs of implementing climate-resilient practices and technologies (Karanja Ng'ang'a et al., 2017). Commercialized maize farmers may also have easier access to funding, market information, and agricultural extension services, all of which are necessary for implementing CSA techniques. Investment choices might benefit from having access to resources and information.

Access to climate information

This variable was treated as a dummy with a value of 1 representing a farmer having access to climate information and 0 otherwise. Access here is defined in terms of possession or access to the various communication channels through which climate information can be disseminated such as TV, radio, mobile phone and the internet and through extension. The threshold for having access to climate information is a farmer having at least a TV or radio which are the common media for disseminating climate information. The positive coefficient means that when farmers have access to climate information, their log odds of being willing to invest in climate-smart agricultural techniques rise by 1.748, all other things being equal. When farmers have access to climate information, their likelihood of being willing to invest in climate-smart agriculture is about 5.741 times higher than when they do not. For example, climate information such as daily and seasonal weather or rain forecasts has increased farmers' awareness of climate risks and helped them to make more informed decisions regarding management practices (Antwi-Agyei, Dougill, and Abaidoo, 2021; Djido et al., 2021; Ngigi and Muange, 2022).

This finding suggests the need for improved dissemination of climate information to farmers. Governments, NGOs, and other organizations should work to provide accessible and relevant climate information to farmers to help them make informed decisions about climate-smart practices. Additionally, efforts should be made to improve the capacity of extension services to provide information on climate-smart agriculture and support farmers in adopting these practices.

It is important to emphasise that, the analysis reveals that age positively influences the likelihood of investing in Climate-Smart Agriculture (CSA) practices, while years of farming experience exhibit a negative relationship. This discrepancy can be explained by the fact that older farmers may have greater financial resources, decision-making authority, and a broader knowledge base (Rose et al., 2018), which facilitates investments in innovative practices like CSA. Conversely, extensive farming experience may foster a preference for traditional methods (Šūmane et al., 2018), leading to resistance against adopting new practices. Additionally, more experienced farmers may perceive CSA as a complex or risky investment, further diminishing their willingness to invest (Musyoki et al., 2022; Ngoma et al., 2019; Tong et al., 2019).

The negative constant reflects the baseline tendency of households not to invest in CSA practices without considering other factors. Its statistical significance reinforces the model predictors significantly in influencing CSA investment decisions beyond the baseline. Thus, the negative constant emphasises that CSA investment does not occur spontaneously but requires interventions. This aligns with the study's objective to identify key drivers of CSA investment and suggests actionable areas such as improving access to climate information and extension services for policy. The theoretical basis for the significance of a negative constant term can be found in studies such as Jiri et al., (2016), Klemm and McPherson (2017), and Munteanu et al., 2018).

The findings underscore the dominance of radio for rainfall-related information and the role of television in providing updates on temperature, sunshine, humidity, cessation dates, wind speed, and cloud movement. These findings can be valuable for policymakers and climate service providers in understanding the preferred channels for disseminating climate information to the local population and improving the effectiveness of information delivery. The results also suggest that the Ghana Meteorological Services have been relatively successful in delivering accurate and reliable climate information related to sunlight, humidity, wind speed, and temperature. Respondents perceive the information on these variables obtained from all sources (including the Ghana Meteorological Services) to be of satisfactory quality.

The results also highlight the indigenous climatic knowledge of respondents regarding specific indicators of rainfall. It reveals that there

Variables	Coeff.	S.E.	p-value	Odd ratio
FBO Membership	-0.466	0.366	0.203	0.628
Sex	2.100	0.358	0.000***	8.163
Age	0.158	0.025	0.000***	1.171
Religion (Muslim dummy variable)	-0.343	0.316	0.278	0.710
Marital Status	0.493	0.364	0.175	1.638
Farm Size	0.717	0.216	0.001***	2.047
Years of Farming Experience	-0.106	0.021	0.000***	0.900
Extension Visits	0.774	0.168	0.000***	2.169
Distance to the nearest market	-0.261	0.066	0.000***	1.298
Level of Commercialisation	0.429	0.218	0.049**	1.536
Access to Climate information	1.748	0.330	0.000***	5.741
Constant	-9.466	1.218	0.000***	0.000
Observations				566
-2 Log likelihood				274.4
Cox & Snell R Square				0.465
Nagelkerke R Square				0.694
Chi-square				354.333
p-value				0.000

Source: authors' elaboration from survey 2023

Table 3: Determinants of households willing to invest in csa practices.

is a widespread belief among respondents in the correlation between earthworm activity and rainfall, as well as the reliability of dark clouds amidst strong winds as a signal of imminent rainfall. However, the perception regarding the significance of singing birds and flying insects as rainfall indicators varies across the study districts. These findings provide insights into the local community's understanding of climate patterns and their reliance on traditional indicators. This knowledge can be valuable for improving climate communication and developing effective adaptation strategies in Northern Ghana.

Conclusion

The study highlights the role of Climate Information Services (CIS) in driving Climate-Smart Agriculture (CSA) investments among maize farmers in Northern Ghana. It integrates scientific and indigenous climate knowledge, providing a unique perspective on farmers' adaptation to climate variability. Radio and television are the primary sources of climate information for maize farmers in Northern Ghana, providing reasonably good quality data on key climatic factors. However, perceptions of service quality vary. The study emphasizes the value of indigenous knowledge in complementing formal climate services, Therefore, tailoring climate information to the specific needs of the local community is essential for improving their understanding of weather patterns.

The PCA analysis highlights the significance of different aspects of weather information for farm-level decision-making. The study identifies two underlying constructs of climatic variables: Factor 1 focuses on immediate farm-level decisions, involving daily weather forecasts, and Factor 2 on long-term planning and mitigation against climate hazards. It also highlights the importance of incorporating indigenous knowledge in agricultural decision-making. Thus, emphasising the need for a comprehensive approach to understanding the impact of multiple climatic variables on agricultural practices.

The results additionally underscore the multitude of factors impacting farmers' inclination to allocate resources towards climate-smart agricultural practices. Farmers' decisions are significantly influenced by gender, age, farm size, farming experience, extension visits, market access, commercialisation, and availability of climate data. However, its limitations include limited generalisability, lack of detailed cost-benefit analysis, and self-reported data.

Policymakers can use these insights to enhance CIS accessibility, address gender disparities, and provide financial support. Investing in visual and auditory communication tools can also enhance the transmission of climate information to smallholder farmers. Quality improvement in specific climate information services can be achieved by enhancing the accuracy and reliability of precipitation forecasts, onset of rains, and cessation dates.

Incorporating indigenous knowledge into formal services can enrich the content and foster cultural relevance. Tailoring climate information services to local needs and perceptions is crucial. Capacity-building programs can enhance farmers' understanding of climate information, while regular community feedback mechanisms can assess the effectiveness of climate services. Promoting multi-stakeholder collaboration between meteorological services, local authorities, non-governmental organisations, and community leaders can create a holistic approach to climate information dissemination.

Strategies to promote investment in climate-smart agriculture and access to climate information are critical. These include promoting gender equality in access to resources, tailoring support programs for older farmers, improving market access, encouraging commercialization while focusing on sustainability, enhancing rural communication infrastructure, and providing training programs on climate-smart practices, risk management, and technology adoption. These strategies aim to improve farmers' access to resources, reduce risks, and promote sustainable agricultural practices.

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Agris on-line Papers in Economics and Informatics

Volume XVII Number 1, 2025

The Inclusion of Ecosystem Service in Land Valuation and Impact on Cadastral Land Value – a Case Study

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Abstract

In the Czech Republic, a system of evaluated soil-ecological units (ESEU) is used for soil valuation, where the price is determined on the basis of production potential. In practice, the production potential of soil is also very important for spatial planning because it is used to determine the protection class of agricultural land with regard to the possibility of designating it for non-productive purposes. This paper focuses on the application of an econometric model to determine the effect on soil value in selected cadastral areas when the effect of the non-productive function of soil in the form of retention is taken into account. This is effectively an ecosystem service calculation, as only the production function is included in the ESEU price in the Czech Republic. For the purposes of the paper, three alternative scenarios are chosen in which the production price includes the price for the non-production function in the form of retention, in the amounts of 5%, 10% and 20%. The results show that even a 5% inclusion of soil retention has a significant impact on its price and, more precisely, on its value. The difference between the original value and the shadow value with the greatest effect of water retention at the 20% level is approximately CZK 12.3 million for the Ivančice site and approximately CZK 20.6 million for the Lysá nad Labem site, which indicates the importance of changing the current government methodology. The higher increase for the Ivančice site is due to the higher proportion of more productive ESEU and, at the same time, the higher retention capacity of the main soil units (MSU), which is absolutely necessary for the valuation of agricultural land in the main production areas of the Czech Republic. The results confirm that in these most valuable areas, the increased share of ecosystem components would lead to the greatest increase in the price of agricultural land, which can be considered as an adequate and meaningful result, if only in the context of comparing agricultural land prices between EU Member States. The water retention capacity of the soil is a qualitative indicator of the non-productive function of the soil and is increasingly supported as such.

Keywords

Soil, ecosystems services, hydrological characteristics, econometric modelling, SUR model, land valuation.

Slaboch, J. and Malý, M. (2025) "The Inclusion of Ecosystem Service in Land Valuation and Impact on Cadastral Land Value – a Case Study ", *AGRIS on-line Papers in Economics and Informatics*, Vol. 17, No. 1, pp. 133-148. ISSN 1804-1930. DOI 10.7160/aol.2025.170110.

Introduction

The concept of soil ecosystem services has received considerable attention in the scientific literature and media in recent years. The monetary valuation of these services, called for by many governments and international organisations, is often described as a necessary condition for the conservation of the natural capital represented by soil (Baveye, Baveye and Gowdy, 2016).

Ecosystem services are defined as the benefits that people derive from ecosystems. The application of the ecosystem services concept is intended to promote the development of policies and instruments that integrate social, economic and environmental perspectives. In recent years, the concept has become a paradigm for ecosystem management (Seppelt et al., 2011; Iliopoulos and Damigos, 2024). Programmes of payments for ecosystem services (PES) have proliferated in recent decades, exchanging value for land management practices designed to provide or secure ecosystem services - there are over 550 active programmes worldwide and an estimated US$36-42 billion per year (Salzman et al., 2018). Ecosystem services, and the stock of natural capital that provides them, are critical to the functioning of the Earth's life support system. They contribute both directly and indirectly to human well-being and thus represent part of the total economic value of the planet (Costanza et al., 1997).

Ecosystem services (as mentioned above) are the benefits that people derive from ecosystems. They include provisioning services (water and food), regulating services (flood, drought and soil degradation control, etc.), supporting services (soil formation, nutrient cycling, photosynthesis, biodiversity) and cultural services (cultural and recreational, spiritual, religious and other intangible benefits) (Slizhe et al., 2023). Identifying the potential of ecosystems to provide ecosystem services (ES) is highly dependent on the level of detail and completeness of the baseline ecosystem map. Current instructions for the production of this type of map includes only a few basic types of ecosystems, which function only on a national or international scales and are insufficient for the identification of the full potential of ecosystem services at local or regional scales (Kruczkowska, Solon and Wolski, 2017). In the EU, mapping and assessment of ecosystems and their services, abbreviated as MAES, is considered a key activity for achieving biodiversity targets and informing the development and implementation of related policies in the water, climate, agriculture and forestry sectors (Maes et al., 2016).

Recent interest in the economics of biodiversity and broader ecosystem services has been expressed empirically as a focus on economic valuation. This emphasis has been stimulated by a growing recognition that the benefits and costs of opportunities associated with such services are often superficially reflected, or even ignored, in policy analyses. The valuation of biodiversity and ecosystem services is therefore increasingly seen as a key element of sound decision-making, as reflected in a growing amount of relevant research (Atkinson, Bateman and Mourato, 2012; Tinch et al., 2019).

Prices of marketed goods and services are readily available and are considered to be indicators of their value. However, determining the monetary value of non-marketed goods and services requires the application of specific valuation methods (Deniz and Ok, 2016). Traditionally, project benefits have been assessed using the reproduction cost method (RCM) or cost-benefit analysis (CBA). At present, however, environmental economics offers alternative methods, such as conditional valuation (CV) and others based on stated preferences, whose main advantage is their ability to capture non-utility and future utility values, which are essential for monetary valuation. Comparisons show that CV estimates of net environmental benefits are almost twice as high as estimates obtained using standard methods (Almansa, Calatrava and Martinez-Paz, 2012; Deniz and Ok, 2016; Damayanti, Bambang and Soeprobowati, 2018). Other methods include willingness to pay (WTP) and willingness to accept (WTA). These are the main tools of the conditional valuation (CV) method, and the willingness to pay method in particular is widely used in the valuation of public goods and ecosystem services in many parts of the world (Liu, 2020; Sourokou et al., 2023).

The modified WTS method was subsequently developed. WTS leads to the achievement of a reasonably balanced price through public valuation of the value of public goods or ecosystem services, rather than the cost of production of a provider (Chang and Yoshino, 2017). In particular, it points to the weakness of the main economic approaches to valuation, growth and development. It concludes that the substantial contributions of ecosystem services to the sustainable well-being of people and the rest of nature should be at the heart of a fundamental shift in both economic theory and practice that is needed if we are to achieve social transformation towards a sustainable and desirable future (Costanza et al., 2017).

Water retention in the landscape is a highly relevant issue in the context of climate change, and a number of research studies have looked at it from an ecosystem services perspective. Results from China, for example, show that soil surface moisture changes dramatically with the seasons. Forests, grasslands, croplands and pastures retain more than 80% of the total soil moisture, which plays an important role in water conservation and quality (Deng, Li and Feng, 2011). In the Azores, peat bogs, as water retention structures, promote landscape equilibrium and reduce the frequency of major events such as landslides. However, these ecosystems are facing increasing disturbance and changes in land use that challenge the future security of these critical ecosystem services. Higher elevations and pristine areas represent the largest hydrological reservoirs and natural sources of water management services (Pereira, Mendes and Dias, 2022). Studies have focused on mangrove ecosystems and their impact on the provision of ecosystem services, or the impact of mineral extraction on forest ecosystems (Sannigrahi et al., 2020; Dushin et al., 2020).

As one of the factors of production, soil is primarily associated with agricultural production, which provides food for the human population. Climate change caused by global warming will make this fundamental task increasingly difficult in the coming years, as it is an activity that is highly dependent on and sensitive to climate change. Population growth is another reason (Tesfaye et al., 2015). Therefore, it is imperative to understand the interactions between climate and agricultural production, especially in light of the increased likelihood of droughts, rainfall variability and rising average temperatures (Hui et al., 2013; Orlandi et al., 2020). The impacts of climate change on food production have been examined in numerous studies, which typically differ in their focus on specific crop types (Zhu et al., n.d.; Yang et al., 2021; Gamal, Samak and Shahba, 2021; Zhang et al., 2021). However, climate change also primarily affects ecosystem services, and can have both positive and negative impacts on adaptation (Lungarska and Chakir, 2024). Databases of soil surveys, soil analyses, soil data systems and enterprise soil systems provide tools and a wide range of quantitative and qualitative data and information for valuation. Assessment of soil resources based on pedological and non-pedological scientific databases is essential for decision-making to ensure more sustainable use of soil resources (Mikhailova et al., 2020).

In this context, the term "soil security" is used, which can only be achieved by conserving and improving global soil resources, which requires a reversal of current degradation processes (Bouma, 2015). In addition to climate change, food production is affected by the physical and chemical properties of soil, especially by its hydrological properties. The goal of agricultural production should be sustainable food production, which requires an understanding of the balance between productivity itself and ecological management (Thao et al., 2023).

Agriculture in areas with limited water availability is possible thanks to irrigation. Irrigated agricultural land is expanding and the demand for irrigation water is increasing. However, there is limited understanding of how much water is used for irrigation and how efficient irrigation increases crop productivity under different climatic conditions. Results indicate that soil hydraulic properties have a very strong influence on the assessment and efficiency of irrigation water (Soylu and Bras, 2024).

Food production and biodiversity are more sensitive to changes in arable land and water regulation, and soil retention is more sensitive to changes in vegetation composition (Sannigrahi et al., 2020). Ecosystem services can also influence the value of land in a cadastral area. Results show that if these ecosystem services are not included in the sale price of a plot of land, its value and price are underestimated, encouraging unorganised forms of urban expansion (Paris et al., 2023).

Soil is a very specific factor of production, as its characteristics do not allow it to be reproduced or relocated, and it is limited in extent. For these reasons, it is very important to protect this source of production for future generations (Pérez-Soba et al., 2001). A very sensitive aspect of soil is certainly the determination of an appropriate price for soil (especially agricultural soil). Worldwide, different methodological approaches and valuation systems are used for this purpose, which can differ significantly, especially depending on the definition of the qualitative parameters of the soil, but also on the mechanism for determining the final price of the land. In the European area, there are generally two basic trends in land valuation, which can be characterised as maximally simplifying mechanisms (usually based only on the market price determined by market supply and demand) and systems which, on the other hand, take into account a wide range of soil characteristics/effects. Scientific work thus provides a possible comparison, where the expansion of multi-criteria land valuation systems is likely, in view of the direction of future agricultural policy and the growing importance of agricultural land for food security; see e.g., Tezcan et al. (2020), Asiama et al. (2017), Cay et al. (2010), Choumert and Phélinas (2015), Niroula and Thapa (2005) and Jürgenson (2016).

The two valuation options, in terms of both market and official land prices, are primarily based on the production potential of the agricultural land or other factors (land shape, access to land, etc.). As a result, the resulting price does not include non-productive functions that are important for human society and the biosphere.

It is clear from the above review that ecosystem services are a very broad concept, ranging from water retention in the soil to religious or spiritual benefits. The aim of this paper is to model the change in the value of land plots in two different cadastral areas (selectively chosen to represent typical regions of the Czech Republic) when taking into account the retention capacity of soils, i.e. including the ecosystem service in the total price of the land, in three basic scenarios based on the main soil units (MSU) structure:

1) Inclusion of the effect of holding capacity on production potential at 5%.
2) Including the effect of retention capacity on production potential at 10%.
3) Including the effect of retention capacity on production potential at 20%.

The results of the article can serve as supporting material for the relevant state administration authorities (State Land Office, Ministry of Agriculture). Inclusion of soil retention capacity in ESEU prices would have an impact on the Valuation Decree No. 441/2013 Coll., which will subsequently be reflected in other laws.

Materials and methods

The basis for the valuation of agricultural soils is evaluated soil-ecological units (ESEU), which is recorded in numerical and cartographic documents. The evaluated soil-ecological unit expresses, by means of a five-digit numerical code, the main soil and climatic conditions affecting the productive capacity of agricultural land and its economic valuation. Data on evaluated soil ecological units are provided by the State Land Office in the national database of ESEU. The characteristics of the evaluated soil ecological units and the procedure for their maintenance and updating are determined by the Ministry of Agriculture by decree. In the conditions of the Czech Republic, the ESEU price is used for valuation, which is historically based only on the production function of the soil through the production potential of individual areas. The production potential and the resulting protection classes play an important role in landscape planning and regional development.

The main objective of the presented paper is to incorporate the non-productive function, in the form of soil retention capacity, into the price of individual ESEU and to estimate the increase in land value in two selected cadastral areas according to defined scenarios. The reason for including the non-productive function (retention capacity) is also that some soils may have a low productive potential but at the same time be very valuable for the site in terms of non-productive potential (typically desirable water retention during floods, etc.). In order to determine the prices of ESEU increased by the retention capacity, and thus the value of the land in the cadastral area, the econometric model previously estimated, specified below, was used to determine the effect of retention on the production potential.

A structural econometric model is used to study the effect of soil characteristics on retention capacity and the effect of retention on production potential. The structural econometric model, as opposed to the reduced form model, provides better insights into the marginal effects of the variables used on both retention capacity and production potential. The relationships are deliberately specified as a recursive system of equations, mainly to avoid the endogeneity problem. At the same time, in order to fulfil the objectives of the work, it is necessary to take into account the effect of other influences on the explained retention capacity, which leads to the construction of a recursive model.

To achieve the main objective of the paper, an econometric approach will be used, using a previously published model that will allow for the estimation of changes in production potential when specific soil influences are included. The model has been presented in detail in the publication Land Valuation Systems in Relation to Water Retention (Slaboch and Malý, 2023), however, the model can be simplified as follows:

$$y_{1ij} = \sigma_1 + \beta_{11} * x_{1ij} + \beta_{12} * x_{2ij} + \beta_{12}^{*} * x_{2ij}^{2} + \\ + \beta_{13} * x_{3ij} + \beta_{14} * x_{4ij} + \beta_{15} * x_{5ij} + \\ + \sum_j \alpha_{1j} * D_j + \varepsilon_{1ij}$$

$$y_{2ij} = \sigma_2 + \gamma_{21} * \hat{y}_{1ij} + \beta_{21} * x_{1ij} + \beta_{23} * x_{3ij} + \\ + \sum_k \beta_{26k} * x_{6kij} + \sum_j \alpha_{2j} * D_j + \varepsilon_{2ij} \quad (1)$$

where y_{1i} stands for retention capacity, y_{2i} is production potential and the regressors are: x_{1i} – porosity; x_{2i} – humus; x_{3i} - grain size; x_{4i} – pH CKl; x_{5i} – soil profile depth; and x_{6ki} – is dummy variable for k-th hydrologic soil group. D_j is j-th dummy variable. Then, *i* indexes main soil unite and j climatic region. *α, β, γ* and *σ* are parameters to be estimated.

Each equation of model (1) can be viewed as a least square dummy variable (LSDV) model and is estimated using least square estimator with:

$$X_* = M_d X \quad \text{and} \quad y_* = M_d y \quad (2)$$

where $M_d = I - D(D^T D)^{-1} * D^T$

and X is a matrix of regressors, y is a vector of dependent variable and D is a matrix of dummy variables.

Moreover, we assume the strict exogeneity of regressors in model (1). To avoid potential heteroscedasticity problems related to the biased estimate of the covariance matrix, robust standard errors of the parameters are calculated.

The resulting estimate of the model determining the production potential of the area depending on soil properties was determined as follows (Slaboch and Malý, 2023) (Table 1).

On the basis of the estimate obtained, we quantified the effect of retention on production potential under the assumed scenarios and then precisely quantified the resulting official price of land in the study regions. For this purpose, data from the Research Institute for Soil and Water Conservation (RISWC) are used, which define the ESEU codes for the given cadastral area, including the land area; the results are then compared for both sites and the effect of the price increase for each ESEU on the value of the cadastral area is evaluated.

The aim is therefore to show the influence of the non-productive function (retention capacity) on the selected sites, which in the conditions of the Czech Republic is not included in the valuation, but may have a significant impact on the price in case of inclusion. For the purpose of this article, three alternative scenarios are presented, which may serve as supporting material for the authorities concerned. Inclusion of soil retention capacity in ESEU prices would have an impact on the Valuation Decree No. 441/2013 Coll., which is subsequently reflected in other laws.

For a relevant comparison, we selected sites whose structure and soil properties make them typical regions in the Czech production zones, i.e. key regions for agricultural production.

Site 1 (Ivančice):

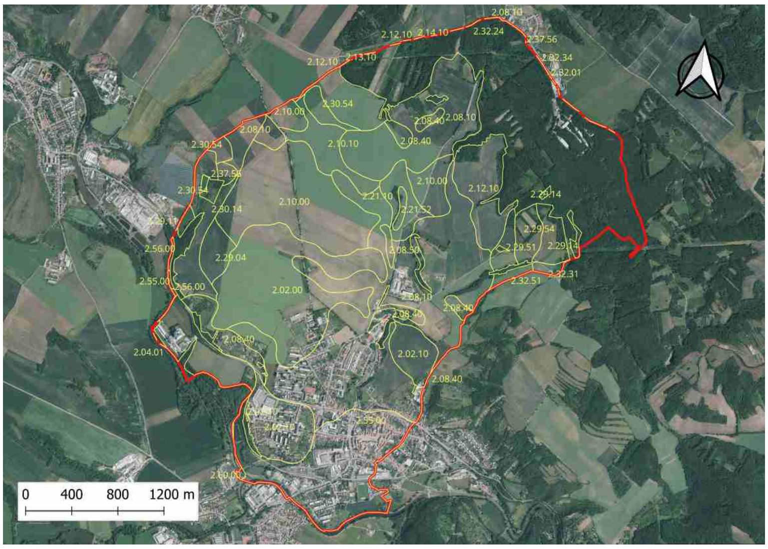
The selected site is detailed in Figure 1, which clearly shows the soil blocks according to the ESEU classification. The entire cadastral area falls within climate region 2.

The total area of the second study site is 1531.26 ha. Figure 2 below shows its detailed structure. The structure of the MSUs affects the overall value of the selected site, so the structure, including the categorisation into protection classes, is described below. It is clear that the largest share of the cadastral area is occupied by MSU 55,

Number of obs. = 486						
F(15,470) = 239.55						
Prob > F = 0.0000						
R-squared = 0.7254						
Root MSE = 11.377						
Prodpot	Coefficient Coefficient	Std. err.	t	P>|t|	[95% conf. interval]	
Retention_predicted_0	0.11231	0.005626	19.970	0.000	0.10126	0.123368
Granularity	0.53909	0.709976	0.760	0.448	-0.85603	1.934211
Porosity	0.38512	0.066809	5.760	0.000	0.25384	0.516399
HSP_A	18.31641	3.062413	5.980	0.000	12.29869	24.334120
HSP_B	16.00687	1.885650	8.490	0.000	12.30152	19.712210
HSP_C	12.85021	2.047846	6.270	0.000	8.82614	16.874280
KR						
1	-6.45611	1.73492	-3.720	0.000	-9.8653	-3.04695
2	1.43243	3.62493	0.400	0.693	-5.6906	8.55551
3	1.11994	1.62536	0.690	0.491	-2.0739	4.31380
4	-8.34180	1.60658	-5.210	0.000	-11.4864	-5.19722
5	-8.08002	1.67247	-5.030	0.000	-11.2370	4.92306
6	-6.56621	1.67247	-3.930	0.000	-9.8527	-3.27976
7	-12.24967	1.63649	-7.490	0.000	-15.4654	-9.03393
8	-16.83460	1.82562	-9.220	0.000	-20.4220	-13.24720
9	-24.41644	2.12075	-10.100	0.000	-25.5838	-17.24912
_cons	21.99123	5.21171	4.220	0.000	11.7501	32.23237

Source: own estimation according to data from RISWC (Slaboch and Malý, 2023)

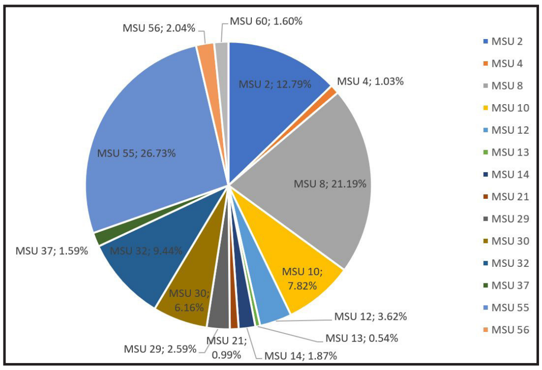
Table 1: Econometric model for calculating the production potential of individual MSU in climatic regions.



Source: own processing, RISWC

Figure 1: Cadastral area - Invančice.

which occupies 26.73%, or 409.24 ha in absolute terms. The genetic soil representatives of MSU 55 are psephitic fluvisol, arenic fluvisol, stratified fluvisol, gleyed fluvisol, arenic phaeozem and arenic colluvisol. These are soils with average to slightly above-average production potential, but classified within KR0-KR4, among soils at risk of wind erosion with lower retention capacity. MSU 8 occupies a significant share (21.19%), with an absolute area of 324.48 ha. Its genetic soil representatives are modal chernozem, modal brown earth, luvic brown earth and modal luvisol. These are soils with average to slightly above average production potential and high retention capacity. MSU 2 has the third highest share, namely 12.79%, covering 195.88 ha in absolute terms. The genetic soil representatives of MSU 2 are luvic chernozems and weakly gleyed luvic chernozems. These are soils with very high production potential and high retention capacity. The MSU 10 and 32 are noteworthy in terms of their proportions. The share of MSU 32 is 9.44%, covering 144.58 ha in absolute terms. Its genetic representatives are modal to mesobasic cambisols and arenic cambisols, including weakly gleyed variants. These soils have average to slightly above average production potential with low retention capacity. MSU 10 occupies 7.82% of the area, which is 119.71 ha in absolute terms. The genetic soil representatives are modal brown earth and modal weakly gleyed brown earth. These are soils with high to very high production potential and high retention capacity. The proportion of other MSU on the selected site is very low, ranging from 1.03 to 6.16%. MSU 30 occupies 6.16% of the cadastral area, or 94.3 ha in absolute terms. The genetic representatives are modal to mesobasic cambisol, pararendzina modal and pararendzina cambic. These are soils with average production potential and average retention capacity. MSU 12 occupies 3.62% of the cadastral area, or 55.4 ha in absolute terms. The genetic representatives are brown earth modal, cambisol modal and luvic cambisol. These are soils with average to slightly above average production potential and high retention capacity. MSU 29 occupies 2.59% of the cadastral area and 39.7 ha in absolute terms. The genetic representatives are the cambisol modal and the cambisol mesobasic. These are soils with average to slightly above average production potential and higher retention capacity. MSU 56 occupies 2.04% of the cadastral area and 31.2 ha in absolute terms. The genetic representatives are modal and mesobasic fluvisol, cambrian fluvisol and colluvisol modal. These are soils with slightly above average to high production potential and high retention capacity. MSU 14 occupies 1.87% of the cadastral area, or 28.6 ha in absolute terms. The genetic representatives are luvisol modal and brown earth luvic. These are soils with slightly above average to high production potential and high retention capacity. MSU 60 represents 1.60% of the cadastral area and 24.4 ha in absolute terms. The genetic representatives are modal chernitzas, chernitzas arnica and chernitzas fluvic. These are soils with very high production potential and high retention capacity. MSU 37 occupies 1.59% of the cadastral area and 24.3 ha in absolute terms. The genetic representatives are cambisol lithic, ranker modal and parendzina lithic. These are soils with low to average production potential and very low retention capacity. MSU 4 occupies 1.03% of the cadastral area, or 15.7 ha in absolute terms. The genetic representative is black earth arenaceous. These are soils with average to slightly above average production potential and low retention capacity. MSU 21 has a share of 0.99% of the cadastral territory, in absolute terms it is 15.1 ha. The genetic representatives are cambisol arenic, pararendzina arenic and fluvisol arenic. These are soils with slightly below average to average production potential and very low retention capacity. MSU 13 has a share of 0.54 % of the cadastral area, in absolute terms it is 8.3 ha. The genetic representatives are brown earth modal, luvisol modal, fluvisol modal and fluvisol stratified. These are soils with slightly above average to high production potential and medium retention capacity. See Figure 2 for more detail.



Source: own processing

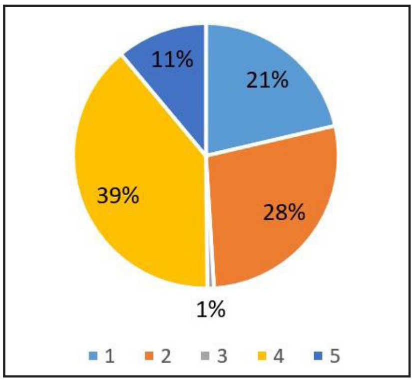
Figure 2: Relative structure of main soil units (MSU) – cadastral area Ivančice.

The current legislation (Decree No. 48/2011 Coll.) establishes protection classes for individual blocks of soil, precisely in relation to the level of production potential. These protection classes have a significant impact on spatial planning within municipalities and urban areas, while soils with high production potential can hardly be used for non-agricultural purposes, typically in the context of conversion to building land, etc. There are five classes of protection for agricultural land:

I. Class I: The most valuable soils in individual climatic regions, mainly in flat or slightly sloping areas, which can only be withdrawn from the agricultural land fund in exceptional cases, mainly for projects related to restoring the ecological stability of the landscape or for linear constructions of fundamental importance.
II. Class II: Agricultural soils with above-average productive capacity within individual climatic regions. With regard to the protection of agricultural land, these soils are highly protected, only conditionally withdrawable and with regard to landscape planning only conditionally developable.
III. Class III: Soils with average productive capacity and medium level of protection, which can be used for development in landscape planning.
IV. Class IV: Soils with predominantly below average productivity within the relevant climatic region and with limited protection, suitable for development.
V. Class V: Soils with very low productive capacity, including shallow, very sloping, hydromorphic, gravelly to stony soils and soils highly susceptible to erosion. These are mostly agricultural soils that are not suitable for agricultural use. More efficient non-agricultural uses can be expected for these soils.

It is clear from the above that the determination of the production potential and the protection class derived from it play a crucial role in spatial planning and regional development. Production potential affects the price itself: the higher the production potential, the higher the price of the ESEU. Current practice has been to use the official values of production potential, but these are seriously outdated (often more than 20 years old) and do not correspond to changes in the landscape and geoclimatic development. Another relatively common problem is the lack of production potential values for newly created soil blocks or re-evaluated soil units.

The detailed structure for the cadastral area of Ivančice is shown in Figure 3. The figure shows that 49% of the cadastral area falls into protection classes I and II, i.e. soils with high to very high production potential, which in absolute numbers amounts to 750.69 ha. Only 1% of the cadastral area is in protection class III. The remaining 50% of the cadastral area is occupied by soils with below average to very low production potential (protection classes IV, V), typically without agricultural use.



Source: own processing

Figure 3: Structure of protection classes – cadastral area Ivančice.

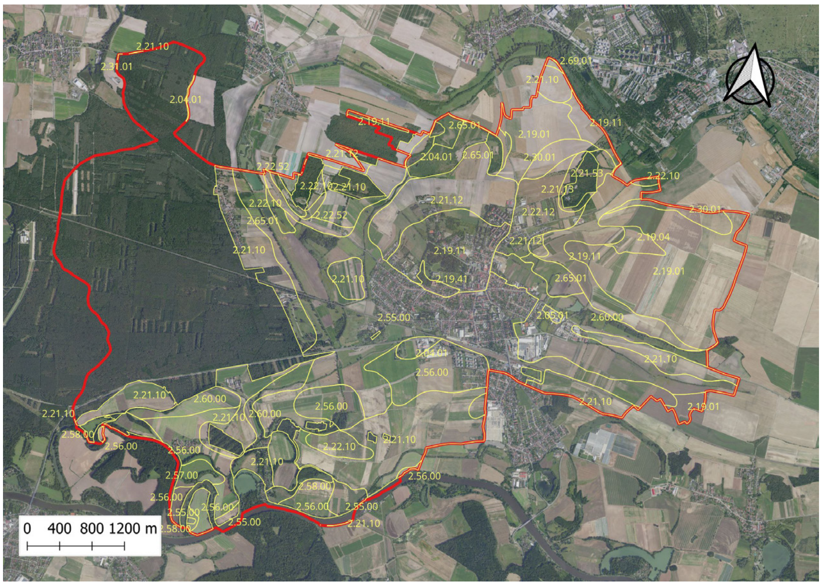
Site 2 (Lysá nad Labem):

The selected site is detailed in Figure 4, which clearly shows the soil blocks according to the ESEU classification. The entire cadastral area falls within climate region 2.

The total area of the cadastral territory of Lysá nad Labem is 5090.02 ha. Figure 5 shows that it contains 15 different main soil units (MSU). The structure of the MSU affects the total value of the selected area, therefore the structure, including the categorisation into protection classes, is described below. MSU 21 has the largest share (38.03%), covering 1936 ha in absolute terms. The genetic soil representatives of MSU 21 are arenic cambisol, arenic regosol, arenic pararendzina and arenic fluvisol. These are soils with average production potential, but they are classified within KR0-KR4, among the soils at risk of wind erosion with lower retention capacity.

The second highest share is held by MSU 19, namely 30.43%, covering 1549 ha in absolute terms. Thus, these two dominant MSUs account for almost 70% of the size of the cadastral area under study. The genetic soil representatives of MSU 19 are modal pararendzina, cambic pararendzina and bleached pararendzina. These are soils with average to slightly above average production potential. These soils are not threatened by wind erosion and have an average retention capacity.

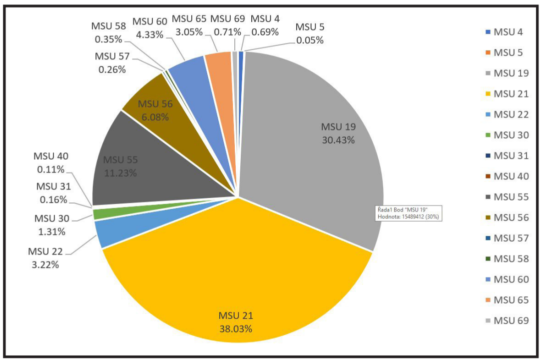
MSU 55 has the third highest share, namely 11.23%, with an absolute area of 571 ha. The genetic soil representatives of MSU 55 are psephitic fluvisol, arenic fluvisol, stratified fluvisol, gleyed fluvisol, arenic phaeozem and arenic colluvisol. These are soils with average to slightly above-average production potential, but within KR0-KR4, soils at risk of wind erosion with lower retention capacity. The proportion of other MSU on the selected site is very low, ranging from 0.05 to 6.08%. MSU 56 occupies 6.08% of the cadastral area, or 309.5 ha in absolute terms. The genetic representatives are fluvisol modal to mesobasic, fluvisol cambic to mesobasic and colluvisol modal. These are soils with medium to high production potential and high retention capacity. MSU 60 accounts for 4.33% of the cadastral area and 220.3 ha in absolute terms. The genetic representatives are modal chernitzas, chernitzas arnica and chernitzas fluvic. These are soils with very high production potential and high retention capacity. MSU 22 occupies 3.22% of the cadastral area, or 163.8 ha in absolute terms. The genetic representatives are cambisol modal, cambisol psephitica, leptosol modal and leptosol psephitica. These are soils with below average to average production potential and lower retention capacity. The MSU 65 occupies 3.05% of the cadastral area and 155.2 ha in absolute terms. The genetic representatives are modal to aquic gley, peaty gley, histic gley and organosol. These are soils with low to below average production potential and low retention capacity. MSU 30 occupies 1.31% of the cadastral area, or 66.4 ha in absolute terms. The genetic representatives are cambyseol modal to mesobasic, pararendzina modal and pararendzina cambic. These are soils with average production potential and average retention capacity. MSU 69 occupies 0.71% of the cadastral area, or 35.9 ha in absolute terms. The genetic representatives



Source: own processing, RISWC

Figure 4: Cadastral area – Lysá nad Labem.

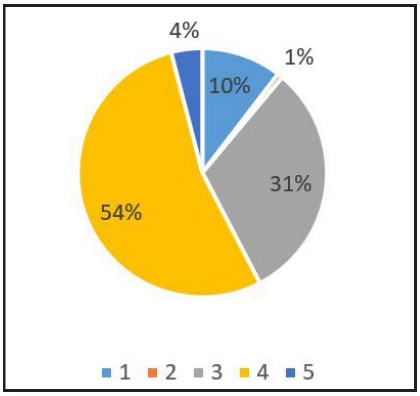
are the aquic gley, histic gley and the organosol. These are soils with very low production potential and very low retention capacity. The MSU 4 occupies 0.69% of the cadastral area, or 34.8 ha in absolute terms. The genetic representative is black earth arenaceous. These are soils with average to slightly above average production potential and low retention capacity. MSU 58 occupies 0.35% of the cadastral area, or 18.07 ha in absolute terms. The genetic representatives are gleyed fluvisol and weakly gleyed fluvisol. These are soils with average to above average production potential and medium retention capacity. MSU 57 occupies 0.26% of the cadastral area, or 13.4 ha in absolute terms. The genetic representatives are eubasic to mesobasic fluvisol and clayic colluvisol. These are soils with medium to high production potential and high retention capacity. MSU 31 occupies 0.16% of the cadastral area, or 8 ha in absolute terms. The genetic representatives are cambisol arenic to mesobasic, pararendzina arenic and pararendzina cambic. These are soils with average production potential and low retention capacity. MSU 40 occupies 0.11% of the cadastral area, or 5.3 ha in absolute terms. The genetic representatives are all soils with a slope of more than 12 degrees. These are soils with very low to below average production potential and low retention capacity. MSU 5 occupies 0.05% of the cadastral area, or 2.7 ha in absolute terms. The genetic representatives are modal chernozem, luvic chernozem and modal fluvisol. These are soils with above average production potential and medium retention capacity. See Figure 5 for more details.



Source: own processing

Figure 5: Structure of main soil units – cadastral area Lysá nad Labem

Figure 6 below shows the structure of protection classes in the selected cadastral area. It can be seen that only 11% of the cadastral area consists of the most valuable soils with above-average productive capacity (protection classes I, II). Conversely, 58% of the area is made up of soils with below-average or very low productivity (protection classes IV, V). Soils of average production capacity (protection class III) cover 31% of the area.



Source: own processing

Figure 6: Structure of protection classes – cadastral area Lysá nad Labem.

Results and discussion

This section characterises the results of the effect of soil retention on the determined price for the cadastral areas defined above using the specified production potential model. Including the ecosystem service of soil retention capacity generally changes the prices of individual ESEUs in the area, which has a positive impact on the resulting soil value quantified on two study sites.

Site 1 - Ivančice

Table 2 works with the quantified land price increase due to the defined scenarios of including the ecosystem component for Site 1. The first column divides the selected area into protection classes, the second column indicates the size of the area (m2), the third column indicates the value of the cadastral area according to the currently valid valuation decree, and the last columns calculate the value including the soil retention capacity according to the defined scenarios.

Plaas et al. 2019 found that soil biodiversity in Europe is deteriorating as a result of continued agricultural intensification and climate change. Healthy soils help prevent erosion, retain water in the landscape and stabilise crop yields. As noted by Zhao et al. (2022), considering only the production function when managing soil is not advisable in the long run, as it may lead to gradual soil degradation and weakening of other ecological functions. Precisely for this reason, our results focus on increasing the cadastral land value in the light of the soil's retention capacity.

In protection class I, the value of the land is set at CZK 53.284 million by the valuation decree (i.e. the average price is CZK 16.29/m^2). If the valuation includes an increase for retention capacity in the maximum assumed amount of 20%, the price of this protection class would increase to CZK 57.899 million, which is a relative increase of 8.66%, with a new average price of CZK 17.70/m^2.

For protection class II, the quantified value is CZK 52.541 million, with an average price of CZK 12.40 per m^2. Again, from Table 2 it can be seen that a 20% increase in the price of MSU due to retention would result in a value of CZK 58.023 million, which is a relative increase of 10.43%, with a new average price of CZK 13.70 per m^2. The higher price increase compared to protection class I is due to the higher retention capacity of MSU in protection class II.

For protection class III, the base land price is set at 1.269 million CZK, with an average price of 10.33 CZK/m^2; the relatively low value is mainly due to the fact that this protection class covers only 1% of the cadastral area. Taking into account the retention capacity in scenario 3, the value increases to CZK 1,340 million, which is a relative increase of 5.56%, with a new average price of CZK 10.91 per m^2.

As already mentioned, the largest share of the total area of the cadastral area under investigation is occupied by protection class IV (39%). In this case, the base price is CZK 49.755 million, with an average price of CZK 8.31 per m^2. In the last scenario, the value would increase to CZK 51.554 million, which is a relative increase of 3.61%, with a new average price of CZK 8.61/m^2.

Finally, protection class V includes mainly soils with very low production potential, with a base price of CZK 7.590 million (average price of CZK 4.48/m^2). Again, the application of the maximum scenario leads to an increase in value to CZK 7.971 million, which is a relative increase of 5.02%, with a new average price of CZK 4.71 per m^2. In summary, for Site 1 it can be concluded that the inclusion of ecosystem services at the 20% level would increase the total value of the cadastral area from CZK 164.441 million to CZK 176.788 million, which is a non-negligible relative increase of 7.51%.

Site 2 – Lysá nad Labem

Table 3 works with the quantified soil price increase due to the defined scenarios of including the ecosystem component for Site 2. The first column divides the selected area into protection classes, the second column indicates the size of the area (m^2), the third column indicates the cadastral value of the area according to the current valuation decree, and the last columns calculate the value including the soil retention capacity according to the defined scenarios.

In protection class I, the current land value is set at CZK 80.921 million (i.e. the average price is CZK 15.27/m^2) by the valuation decree. Taking into account a 20% increase for retention capacity, the value rises to CZK 88.185 million, i.e. a relative increase of 8.97%, with a new average price of CZK 16.64/m^2. For protection class II, the calculated value is CZK 3.703 million; in this case, the average price in this class is CZK 10.81/m^2. Again, from Table 1 it can be seen that a 20% increase in the ESEU price due to retention would result in a value of 3.973 million CZK, which is a relative increase of 7.28%, with a new average price of 11.60 CZK/m^2.

For protection class III, the calculated value is CZK 174.165 million, with an average price of CZK 10.94/m^2. The high value is due to the fact that this protection class accounts for 31% of the assessed cadastral area. Taking into account the retention capacity under Scenario 3, the value increases to CZK 181.825 million, which is a relative increase of 4.39%, with a new average price of CZK 11.42/m^2. As already mentioned, the largest share of the total area of the cadastral territory is occupied by protection class IV

Protection class	Area (m^2)	Cadastral area value	Cadastral area value - 5R	Cadastral area value - 10R	Cadastral area value - 20R
1	3271166	53 284 415	54 438 122	55 591 829	57 899 243
2	4235727	52 541 838	53 912 224	55 282 611	58 023 384
3	122869	1 269 570	1 287 218	1 304 866	1 340 161
4	5988848	49 755 174	50 204 912	50 654 651	51 554 128
5	1693985	7 590 384	7 685 780	7 781 176	7 971 967
Sum	15312595	**164 441 383**	**167 528 258**	**170 615 134**	**176 788 885**

Source: own processing

Table 2: Cadastral area value – Ivančice (CZK).

Protection class	Area (m^2)	Cadastral area value	Cadastral area value - 5R	Cadastral area value - 10R	Cadastral area value - 20R
1	5298723	80 921 311	82 737 476	84 553 641	88 185 972
2	342490	3 703 284	3 770 761	3 838 238	3 973 191
3	15918500	174 165 949	176 080 714	177 995 479	181 825 008
4	27285397	156 164 040	157 449 928	158 735 817	161 307 594
5	2057183	6 984 961	7 047 435	7 109 909	7 234 857
Sum	50902293	**421 939 548**	**427 086 317**	**432 233 085**	**442 526 622**

Source: own processing

Table 3: Cadastral area value – Lysá nad Labem (CZK).

(54%). In this case, the calculated value is CZK 156.164 million, with an average price of CZK 5.72/m^2. In the last scenario, the value would increase to CZK 161.307 million, which is a relative increase of 3.29%, with a new average price of CZK 5.91/m^2.

Finally, protection class V, which is intended for soils with very low production potential, is worth CZK 6.984 million and the average price is CZK 3.40 per m^2. Again, the application of the last scenario leads to an increase in value to CZK 7.234 million, which is a relative increase of 3.57%, with a new average price of CZK 3.52/m^2. Looking at the total value of the cadastral area, it increases from CZK 421.939 million to CZK 442.526 million, which is a relative increase of 4.87%.

An overall comparison of the two selected sites clearly shows that the main effect of including ecosystem services is to significantly change (increase) the value of the land in the area, which applies equally to both sites. The difference between the sites lies in the dynamics of the increase, which is mainly influenced by the different structure/representation of the different protection classes; nevertheless, two main effects can be observed from the results of Tables 2 and 3. At the same time, the relative increase in the proportion of water retention is not directly proportional to the relative increase in price, which ultimately leads to a faster rate of price increase for site 1, although the differences between the assumed scenarios are greater in absolute terms.

An assessment of the hydrological cycle and water retention in wetland soils has been carried out in Mexico and found different retention capacities for different soil types (Cejudo et al. 2024). However, the study did not quantify the monetary value of these ecosystem services.

Ecosystem service valuation has also been carried out in China, specifically in the Guangdong-Hong Kong-Macau Greater Bay Area. In this case, several ecosystem services were valued, in particular habitat quality, carbon storage and soil retention. The results show that the total value of ecosystem services for the area was 4.2 billion yuan, and the results are applicable to ecological compensation in urban agglomerations (Wu, Huang and Jiang, 2022). It is clear that ecosystem services can have a very significant value for a given area.

Therefore, many studies have addressed ecosystem services (including soil retention capacity) from the perspective of urban agglomeration development (Zhang et al., 2022) or disproportionate development of forest or arable land (Yan and Li, 2023).

In the EU, mapping and assessment of ecosystems and their services, abbreviated as MAES, is considered a key activity to achieve biodiversity targets and to inform the development and implementation of related water, climate, agriculture and forestry policies (Maes et al., 2016).

Soil retention capacity is also influenced by climate change, landscape composition and land use. From this perspective, it is important to identify the drivers of ecosystem services in a global context, thus providing a practical tool for soil management (Bai, Ochuodho and Yang, 2019).

Conclusion

The main objective of the paper was to demonstrate the importance of including soil retention capacity in the land pricing mechanism, especially with regard to the ever-increasing demands of soil water management in agricultural production, but also from the perspective of environmental protection in the context of current climate change. The current system of official land prices, based on normative methods with fixed evaluation criteria, obviously has many advantages, including the relative simplicity and clarity of expressing the value of a selected block of soil. However, the current changing natural conditions are leading to radical changes, both geoclimatic and ultimately economic, and it is probably highly desirable to analyse and respond to these changes. One of the primary and vital aspects is the issue of water availability and management, which is closely linked to soil management, as agricultural land is a crucial factor in water retention in the landscape and its continued agricultural productive use.

In the context of these changes, the current system of soil evaluation appears to be at least inflexible, or even outdated and inappropriate, because parameters related to water absorption and retention capacity of soils are minimally or not at all reflected in the existing system. Therefore, the main objective of this paper was to determine the influence of the non-productive function of soil in the form of retention on the value of land in a case study of two production significant areas of the Czech Republic. The results show that even a small increase in the share of the water retention indicator in the soil price quantification methodology has a significant impact on its value. We analysed three alternative scenarios (5%, 10% and 20%); all options increased the original quantified prices by millions of crowns per site. The difference between the original price and the shadow price with the highest share of water retention at the 20% level was approximately CZK 12.3 million for the Ivančice site and approximately CZK 20.6 million for the Lysá nad Labem site, indicating the importance of changing the current government methodology, as the water retention capacity of soils is and will be increasingly supported as a qualitative indicator. With regard to the production function of soil, the results obtained support the idea of including ecosystem service elements in the land price calculation mechanism. At the same time, it can be implicitly concluded that the importance of soil water retention will be strongly reflected in the non-production function of soil in the near future, as a highly valued means of protecting the landscape and people in the face of increasingly urgent climate variability.

The present results also point to the suitability or interrelationship of other study parameters, as can be seen from the comparison of the two sites, which showed a noticeable difference in the increase of the cadastral area value. The higher increase for the Ivančice site is caused by the higher proportion of more productive ESEU and, at the same time, the higher retention capacity of the MSU, which is absolutely essential for the valuation of agricultural land in the main production areas of the Czech Republic. The results confirm that in these most valuable areas the increased share of ecosystem components would lead to the greatest increase in the price of agricultural land, which can be considered an adequate and meaningful result, if only in the context of the comparison of agricultural land prices (still relatively low in the Czech Republic) among EU Member States.

Acknowledgments

This paper was created within the framework of the project NAZV QK22020130 – Implementace inovací BPEJ do systému státní správy. Supported by the Ministry of Agriculture of the Czech Republic. Programme of Applied Research of the Ministry of Agriculture for the period 2017-2025, ZEMĚ.

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Agris on-line Papers in Economics and Informatics

Volume XVII Number 1, 2025

Agris on-line Papers in Economics and Informatics

The international reviewed scientific journal issued by the Faculty of Economics and Management of the Czech University of Life Sciences Prague.

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ISSN 1804-1930