Designing a Socio-Ecological Value Scorecard: A Holistic Approach to Farm Performance and Sustainability

Saeed Niksaz(✉) and Fisnik Dalipi

Linnaeus University, Kalmar, Sweden
{saeed.niksaz,fisnik.dalipi}@lnu.se

Abstract. Data-driven digital technologies in agriculture are revolutionizing the industry by enabling precision farming, improving decision-making, and promoting sustainability. However, achieving sustainability remains challenging due to technical, policy, economic, and social barriers that prevent the adoption of data-driven approaches. Furthermore, the diversity of ecological and social situations requires adaptations of climate-smart agricultural practices. This paper posits that the socio-ecological value scorecard can serve as a transformative tool to address these challenges. By integrating environmental, social, and economic measures, the value scorecard can provide a comprehensive framework for evaluating and improving agricultural practices. It emphasizes the importance of data-driven measures for managing sustainability for farmers, which depend on understanding how they use this information and how it can help them. Hence, this position paper argues that the design of a socio-ecological value scorecard has the potential to enhance farming performance by adopting state-of-the-art technologies, foster sustainability, and overcome structural challenges in agriculture. Moreover, designing a dashboard for a socio-ecological value scorecard is essential to provide farmers and stakeholders with an intuitive, visual tool that integrates diverse data sources across environmental, social, and economic domains, enabling them to make informed decisions and drive sustainable agricultural practices.

Keywords: Socio-ecological value scorecard · Data-driven digital technologies · Sustainability · Productivity · Data sharing · Data analysis · Innovation · Business model

1 Introduction

Since the world faces rising food security concerns, the adoption of digital technologies is imperative for maintaining a sustainable and resilient food supply. These digital technologies provides a range of advantages, including improved efficiency, more transparency, enhanced sustainability, and increased resilience [1]. Digital transformation reshape how costs, benefits, and responsibilities are distributed within a system and prompting stakeholders to take action to decrease adverse effects [2]. However, despite their potential, digital technologies also encounter challenges in domains related to

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economy, data security, accessibility, and integration. Key issues include the need for stakeholder training, confirming the technology functions in various settings, automating implementation to protect distinct landscape features, and acquiring new skills [3]. In addition, factors such as affordability, accessibility, privacy, security, and the technical complexity of the technology must be carefully considered when implementing digital solutions in the agricultural sector [4].

The shift toward digital agriculture is a multifaceted and evolving process that requires the active engagement of various stakeholders [5]. Data-driven approaches assists stakeholders in optimizing land-use patterns, selecting suitable crop varieties, and managing agroecosystem activities [3]. Yet, a key obstacle in this transformation is the insufficient participation and collaboration between stakeholders, which hinders progress. When the benefits accrued by agricultural operators from adopting digital transformation are inadequate or detrimental, they may be reluctant to participate, which can impede the advancement of agricultural digitalization.

To address these challenges, this study introduces the socio-ecological value scorecard as a transformative tool for assessing and improving farm performance across key dimensions such as quality, cost reduction, waste management, and CO2 emissions. The socio-ecological value scorecard evaluates farming operations through a holistic lens, combining environmental, social, and economic measures. This research also highlights how using the socio-ecological value scorecard can change the way we measure farm success, making agriculture both profitable and environmentally sustainable. Moreover, the study advocates for practical policies and targeted investments to widespread adoption of this approach in sustainable farming. Furthermore, this study explores how different data sources, stakeholders, and data governance in agricultural sector can come together to build this scorecard. By analyzing community-based business models within in this ecosystem, system thinking is used to address the complexity of this dynamic environment.

The rest of this paper is organized as follows. Section 2 introduces the Socio-Ecological Value Scorecard, detailing its concept, components, and integration of environmental, social, and economic factors to enhance farm performance. Section 3 explores the role of data and digital technologies, specifically Artificial Intelligence (AI), Internet of Things (IoT), and digital platforms in supporting scorecard implementation. Section 4 discusses the challenges and solutions related to implementation, encompassing technical, economic, social, and cultural factors, along with strategies from state-of-the-art literature. Section 5 explores policy implications, including necessary policy support, data privacy and security concerns, and the promotion of education and awareness. Finally, Sect. 6 presents the future outlook and conclusions, the potential impact on sustainable agriculture and issuing a call to action for stakeholders.

2 The Socio-Ecological Value Scorecard

As recommended in the Green Charter [6], developing a socio-ecological value scorecards for farms that includes environmental impact assessment is of high importance. This allows to increase further value of data to farms aiming to amplify data sharing. The scorecard will include measure on improving quality, reducing business costs, reduce waste and reducing CO2 emission.

2.1 Concept and Components

The socio-ecological value scorecard is a conceptual model designed to evaluate both the social and environmental impacts of farming. It looks at different aspects of sustainability, productivity, profitability, and governance. In addition, it helps stakeholders and decision-makers to see the benefits and challenges of different choices, which allows them to collaborate with each other towards reaching both short-term and long-term goals. Economic measures focus on profitability, financial stability, and access to markets. Moreover, one of the fundamental principles underpinning the socio-ecological value scorecard is that governance and support policies ensure alignment with sustainability regulations. Conversely, the adoption of technology facilitates precision agriculture and edge AI, which enhance sustainability.

2.2 Integration of Environmental, Social, and Economic Factors

The evaluation process should look at both data and opinions to get a full understanding. Data such as carbon emission, water quality, and waste produced, give clear details on environmental sustainability. At the same time, opinions, like how people view the situation, traditional knowledge, and cultural importance, add extra conditions [7]. Each factor is given a score based on how important it is to help providing a comprehensive view of sustainability. The socio-ecological value scorecard is built on the concept of systems thinking. It means that farming practices are assessed through a multi-faceted perspective that combines environmental, social, and economic considerations.

2.3 Potential Benefits for Farm Performance

As shown in Fig. 1, a high-level architecture of smart agriculture is illustrated to grasp the interaction of different components to collect, process, and adopting data for informed decision-making. In this architecture, remote sensors, drones, satellite imagery, and IoT devices monitor pivotal agricultural elements such as temperature, soil moisture, crop conditions, livestock health, and machinery performance. These devices, as illustrated in Stage 1, collect raw data for real-time monitoring.

A key part of this model is its ability to adjust and respond to changes. Agricultural ecosystems are always changing, so it is imperative to monitor and update sustainability plans regularly through digitalization [8]. The value scorecard includes feedback loops that let us check and adjust the measures and their score over time. Involving the community and using participatory methods is important to make sure the scorecard stays helpful.

In Stage 2, the collected data is shared either via wireless or wired devices through communication networks, including Wi-Fi, or LoRaWAN, to a central processing system [9].

At the data governance and storage phase, which is Stage 3, data is processed through AI and machine learning models to derive actionable information. Moreover, technologies such as blockchain are adopted to secure the shared data. This stage generally performed in cloud systems and databases. Consequently, the processed data are visualized through analytics dashboards for end-users in stage 4, particularly farmers, policymakers, and service providers, to access the information and make data-driven decisions. Farmers apply this knowledge to optimize practices like irrigation, fertilization, and pesticide management. Policymakers can refine policies and regulations. At the same time, service providers deliver appropriate innovations needs according to this data. The data generated in this architecture is invaluable, serving as the foundation for predictive analytics, sustainability assessments, and risk management. It facilitates proactive measures to address challenges such as droughts or pest outbreaks, while also contributing to research and innovation in farming practices. The architecture shows the importance of data sharing among farmers, policymakers, and service providers to foster collaboration and innovation. This promotes transparency, aligns supply chain activities with regulatory frameworks, and ensures mutual benefit across stakeholders. However, effective data sharing requires security and privacy measures to protect sensitive information. This architecture represents how smart agriculture integrates data collection, processing, and visualizing to boost informed decision-making and support the objectives of the socio-ecological value scorecard.

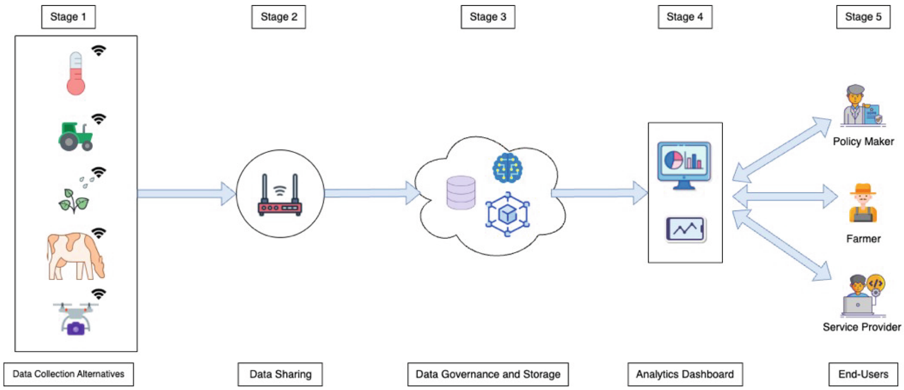

Fig. 1. High-level architecture in smart agriculture

3 The Interplay Between Technology and the Socio-Ecological Value Scorecard

The design of a socio-ecological value scorecard has the potential to enhance farming performance by adopting state-of-the-art technologies, foster sustainability, and overcome structural challenges in agriculture. It not only aligns with digital innovation but also fosters resilience and sustainability by incorporating innovation and changes in business model. Also, the socio-ecological value scorecard fills the gap between technological potential and practical application which enable farmers to make informed decisions tailored to their intents.

3.1 Role of Data and Digital Technologies

Digitalization is generally understood as the shift toward technologies connected with the Fourth Industrial Revolution (4IR) [10, 11]. This transformation encompasses innovations such as the IoT, AI, cyber-physical systems (CPS), virtual reality (VR), and augmented reality (AR), along with various mobile technologies, devices, and applications [12]. This revolution technologies has led to the development of concepts such as "Smart Agriculture," "Digital Farming," and "Agriculture 4.0," all of which emphasize the internal and external connectivity of farming operations [13].

A key feature of this transformation is enabling the availability of information to all agricultural stakeholders [14]. Stakeholder communication is conducted electronically, while data management, processing, and analysis are mostly automated [10]. Furthermore, Internet-based technologies ease the efficient handling of large datasets and boost connectivity throughout the agricultural value chain [15].

In agriculture, digitalization can be seen as having significant possibility to transform farming practices and production processes and enhance value chain management [16]. Moreover, the necessity to alleviate climate change has driven efforts regarding innovative solutions [2]. By integrating blockchain, IoT, big data, and AI, digitalization plays an important role in shaping a more sustainable planet by facilitating environmentally friendly advancements.

In smart farming, remote performance monitoring systems help in decision-making by bringing different types of data together in one centralized platform. These tools collect, visualize, and analyze various forms of agricultural data, including climate patterns, crop health measures, soil conditions, and economic benefits [17]. By combining this information, dashboards facilitate data-driven decision-making, ensuring that stakeholders such as farmers, policy makers, and service providers have access to actionable vision that increase productivity and sustainability.

The remarkable challenges in smart agriculture underscore its nature as a complex, diverse, and heterogeneous system comprising various stakeholders, advanced technologies, and their interactions. This ecosystem encompasses farmers, agribusinesses, technology providers, researchers, and policymakers, each with varying degrees of influence and expertise. In the context of smart agriculture, systems thinking becomes of paramount importance. These stakeholders collaborate to comprehend the holistic performance of the entire agricultural system, rather than focusing on individual components in isolation [18]. This approach emphasizes the interconnectedness of elements such as precision farming technologies, IoT sensors, data analytics, and sustainable farming practices.

The socio-ecological value scorecard can operate as a dashboard in agriculture by means of evaluating and balancing economic, environmental, and social factors. This scorecard provides a more holistic perspective on agricultural performance. Moreover, it would enable policymakers and stakeholders to assess the impact of agricultural practices beyond productivity by integrating factors like environmental supervision and social fairness into decision-making. Therefore, socio-ecological value scorecard can enhance this process through incorporating real-time socio-environmental data and allows stakeholders to assess the broader impact of agricultural decisions on communities and ecosystem health.

3.2 Enhancing Scorecard Implementation

The success of dashboards in agriculture is mostly attributed to their role as unifier across multiple systems [19]. Dashboards consolidate data from diverse sources, such as IoT sensors, weather monitoring systems, and agronomic databases to provide a wide overview of agricultural conditions. Furthermore, they facilitate communication among different stakeholders by offering real-time insights and serving as a platform for collaboration between farmers, scholars, and policymakers. The socio-ecological value scorecard fastens this integration by incorporating qualitative and quantitative measures of agricultural sustainability, making sure that both environmental and social aspects are considered in decision-making.

4 Potential Implementation Challenges and Solutions

Designing and implementing a socio-ecological value scorecard for farming consists of some technical considerations, specifically when implemented in rural areas. These considerations encompass data collection challenges, constraints of digital infrastructure limitations and the incorporation of ecological and social measures [3]. Data collection and accuracy are bringing about substantial challenges. Lack of experience among farmers in data collection and reporting to consider as fundamental challenges because this socio-ecological value scorecard should be practical in these areas.

Data collection and accuracy present significant challenges in rural areas, including inadequate infrastructure and connectivity, limited access to technology and digital skills among farmers, lack of funding, data privacy and security issues, and reluctance of farmers to adopt novel technologies [20]. Potential solutions include utilizing participatory data collection methods by engaging farmers through training programs, implementing remote sensing and GIS technologies to supplement field data, and developing standardized but adaptable data collection protocols to account for local variations.

Digital infrastructure and connectivity also pose critical issues. Many rural areas suffer from poor internet connectivity and lack access to digital tools, while technological literacy among farming communities remains limited. To address these issues, an offline-capable, mobile-friendly application can facilitate data entry. Deploying low-cost, solar-powered IoT sensors can automate environmental data collection, and providing digital literacy workshops with simple, user-friendly interfaces can enhance adoption.

The integration of socio-ecological measures presents further challenges, such as balancing ecological sustainability with economic viability for farmers and harmonizing diverse data sources into a coherent and actionable scorecard. A weighted multi-dimensional assessment framework that integrates expert input and stakeholder perspectives can be developed to address these concerns. Machine learning techniques can be employed to analyze patterns and provide adaptive recommendations, while a modular scoring approach makes it easier to adjust for different regions.

Scalability and adaptability remain significant obstacles, as difficulties in scaling the scorecard across diverse agricultural landscapes and resistance to change from traditional farming communities can hinder implementation. Trial programs in certain rural areas can refine methodology before wider application. Engaging local agricultural cooperatives and extension services can promote the benefits of the scorecard, whereas ensuring flexibility in the model allows for adaptation based on local socio-ecological conditions.

A conceptual model for implementing the socio-ecological value scorecard should integrate stakeholder engagement, data collection methods, a multi-dimension evaluation framework, a technology deployment strategy, and a feedback loop. Stakeholders, including farmers, researchers, policymakers, and local organizations, should be involved in co-developing the scorecard. The model should combine qualitative farmer-reported data with quantitative remote sensing and IoT-enabled monitoring. A dynamic weighting system should balance socio-ecological dimensions, while technology deployment strategies need to fit the local situation and address local infrastructure constraints. Establishing iterative evaluation mechanisms will refine the scorecard over time based on field data and user experience. By addressing these technical considerations, the socio-ecological value scorecard can serve as a robust tool for sustainable agricultural evaluation, particularly in rural regions.

A key challenge in developing resilient innovation ecosystems is identifying the optimal role of research and technology organizations in these networks. This demands fostering broader public-private partnerships and establishing connections with new stakeholders in both the agricultural sector and beyond [21]. Trustworthy and comprehensive data on socio-ecological elements in farming, such as ecological diversity, soil quality, and social welfare, may be limited or incompatible. Many smallholder farms lack data collection, which leads to gaps in assessment [22].

Identifying convenient measures and their corresponding weight in the scorecard is challenging, since socio-ecological values are multi-dimensional and complex [23]. These challenges can be addressed through participatory approach involving farmers, ecologists, and social scientists to bond the selection of balanced measure.

Establishing standardized data collection protocols and leveraging existing databases can help address this issue. Collaborations with local agricultural organizations, IT service providers, and remote sensing technologies can boost data availability and reliability.

In addition, farmers and policymakers may hesitate to embrace the scorecard if they view it as inconvenient or irrelevant to their present needs. Designing the scorecard with farmers and policymakers ensures that it aligns with their targets and incentives.

Metrics act as frameworks for creating, analyzing, and utilizing data [24]. However, there is a need for metrics to be more closely aligned with the structural, practical, and cultural aspects of farming. Socio-ecological values encompass qualitative dimensions that are difficult to quantify. Adopting a mixed-methods approach that combines quantitative metrics with qualitative evaluations provides a holistic assessment of agricultural systems.

Developing and deploying a detailed scorecard requires financial and human experts, which may be constrained in low-income agricultural settings [2]. Seeking funds from government and organizations can provide financial supports. Additionally, utilizing digital tools and open-source software can minimize costs.

Lastly, one major challenge is that a scorecard designed for one area or farming system may not be transferable to others easily due to variations in ecological conditions

[25]. Designing a socio-ecological value scorecard that allows for customization while maintaining core concept can increase scalability.

5 Policy Implications

Accurate and in-depth formal protocols are considered as a major role in facilitating the integration of digital technologies in agriculture, especially within human–robot collaborative systems where safety concerns must be addressed [26]. It is crucial to think about the ethical implications of digital transformation, including the use of robotics in agriculture, particularly in the context of human–robot interaction [27].

The ethical challenges of smart farming can be classified into three main themes: (a) data ownership, access, sharing, and control, (b) power distribution, and (c) societal impacts [28]. One serious area for investigation is the interpretation of data in smart farming systems. While data collection is vital to precision agriculture, its interpretation remains a black box by technology providers, so that ethical concerns about power imbalances and the potential exploitation of farmers' data is raised. Also, the establishment of trust among stakeholders is important for encourage a collaborative environment.

Besides, the General Data Protection Regulation (GDPR), effective from May 25, 2018, significantly impacted global privacy and data protection laws, emphasizing the importance of keep safe personal data [29]. The core principle of the GDPR is that organizations must be responsible for their data processing activities. It mandates greater transparency in how data is collected, used, and monitored.

On the other hand, regulatory frameworks are considered as a crucial part in guiding smart farming practices [28].

The socio-ecological value scorecard must consider issues like data ownership, rights to financial gain from data analysis, and mechanisms for fair data sharing to be effective.

6 Future Outlook and Conclusion

The socio-ecological value scorecard in farming has the potential to transform sustainable agriculture through a comprehensive dashboard for evaluating and raising the environmental, social, and economic aspects of farming practices. It can perform as a decision-making tool for farmers, policymakers, and supply chain actors.

One of the key advantages of this dashboard is its capacity to connect sustainability goals with actionable farming approaches. It helps farmers to balance short-term goals, especially economic, with long-term environmental sustainability. By using this dashboard, farmers will gain actionable insights that promote the adoption of environmentally sustainable practices, resulting in reducing business costs, minimizing waste and lowering CO2 emissions. Moreover, by developing transparency, the scorecard enables consumers to make informed selections. At the center of this innovation is data sharing and governance, which confirm that reliable and consistent data is possible for stakeholders.

Also, governments and international bodies strive to meet climate targets and food security goals because the widespread adoption of such a tool can significantly contribute to achieving equitable agricultural sector.

6.1 Call to Action

To realize the benefits of a socio-ecological value scorecard in farming, it is essential for all stakeholders, particularly farmers, researchers, policymakers, agribusinesses, and consumers, to collaborate in designing, implementation, and continuous improvement.

Farmers. They are at the forefront of implementation and should actively participate in forming the scorecard to guarantee its usefulness and applicability. Providing feedback will be critical for improving the dashboard to maximize its benefits. Besides, farmers should be supported in adopting digital tools that assist data sharing and governance, protecting their data sovereignty and fairness.

Researchers and Academics. Interdisciplinary studies are needed to refine the measures of the scorecard. Universities and research institutions should focus on studies that evaluate the effectiveness of scorecard in various farming practices. Additionally, research should focus on best practices for data governance and sharing to guarantee that shared data supports informed decision-making.

Policymakers and Supply Chain Actors. Policymakers should work closely with farmers to make sure the scorecard aligns with local and national sustainability goals. Furthermore, policies should aid secure and ethical data sharing that increase the transparency and usage of sustainability measures.

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