A conceptual framework for modelling and economic assessment of regenerative agriculture in Australian mixed farming

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Abstract

Regenerative agriculture (RA) is a philosophical approach for the sustainable use of agricultural lands, focusing on improved productivity in the longer term and landscape restoration. Its wider adoption is hindered by multifaceted challenges such as the lack of financial justification for transitioning to RA, exacerbated by uncertainty due to varying definitions, as well as the absence of a bioeconomic assessment framework. This paper establishes a definition for RA and develops a practical modelling framework to enable the economic assessment of RA practices, focusing on Australian mixed farming systems. We reviewed literature on existing RA definitions, assessment methods, and advanced analytics. The review found diverse definitions of RA based on principles, practices, outcomes, or a combination of these elements. The proposed definition highlighted a transdisciplinary approach, integrating local, indigenous and scientific knowledge, with soil, water and organic matter conservation as focal points for fostering soil health, thereby supporting enhanced ecosystems and improved socioeconomic conditions. The review identified potential indicators, tools, models, as well artificial intelligence and machine learning techniques for assessing the bioeconomic outcomes of RA scenarios. A conceptual modelling framework was subsequently developed, including sub-modules for crops, soil, pasture, livestock, and economic evaluation, integrated with identified potential assessment methods. This proposed framework can be refined to handle complex RA scenarios using advanced machine learning and remote sensing techniques. These modifications will enhance flexibility in assessing the profitability and risk associated with implementing RA practices, thereby supporting evidence-based decision-making.

Keywords

Bioeconomics, machine learning, remote sensing, farm profitability, soil health, transdisciplinary approach

Introduction

Modern agricultural practices have significantly contributed to global food security, reducing undernourishment rates from 14.7% in 2000 to 9.9% in 2020 (Grimm and Luck 2023). This success, driven by advancements such as mechanization and synthetic agrochemicals, has come with environmental costs, including soil degradation, water pollution, and greenhouse gas emissions. With the global population projected to reach 8.6 billion by 2030 (McKeon et al. 2015), sustainable farming practices are imperative. Within this context the concept of Regenerative agriculture (RA), with its' emphasis on holistic farming approaches, has emerged as an increasingly popular alternative farming framework (Sands et al. 2023; Khangura et al. 2023).

Regenerative Agriculture focuses on restoring and maintaining soil health, biodiversity, and ecosystem functions (Khangura et al. 2023). The global market for RA reached USD $975 million in 2022 and is expected to achieve at a compound annual growth rate of 15.9% from 2023 to 2030, reaching over USD $4.3 billion by 2032 (Grand View Research 2023). The growing interest in RA is driven by the need for sustainable agricultural practices that mitigate environmental degradation, address climate change, and address food security challenges. However, the absence of a standardized definition, framework, and methods for bioeconomic assessment hinder the widespread adoption of RA practices. There is a significant research gap in Australia concerning the overall outcomes of broadacre farms, particularly in terms of farm economics (e.g., profit and risk) within the context of RA. Assessing farm profitability is vital for evaluating the overall impacts of a transition to RA and significantly influences farmers' decisions (Schreefel et al. 2022). Therefore, this paper aims to address these gaps by evaluating existing RA definitions and proposing a working definition that integrates both socioeconomic and biophysical aspects. Additionally, it examines various indicators, tools, and models used to assess effectiveness of RA, with a particular focus on advanced analytical methods. A conceptual framework for evaluating the bioeconomic outcomes of RA in mixed farming systems in Australia is developed as a case study.

Methods

The methodology comprised two separate systematic reviews and one literature review (Figure 1). One systematic review preliminarily examined the existing definitions of RA. The other identified indicators, tools, and models for assessing the bioeconomic aspects of RA. Both reviews adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al. 2009). Comprehensive search strategies were implemented using the Web of Science (WoS) and Scopus databases to identify relevant publications from 1985 to 2023 (detailed information on search terms can be found in Jayasinghe et al. 2023). A total of 129 and 84 papers were included in the first and second systematic reviews, respectively. The literature review explored alternative methodologies, including advanced analytical methods such as artificial intelligence (AI) and machine learning (ML), which could enhance the accuracy and efficiency of RA assessments and contribute to the development of an RA framework. Finally, a conceptual modelling framework was developed to evaluate the bioeconomic outcomes of RA in mixed farming systems in Australia.

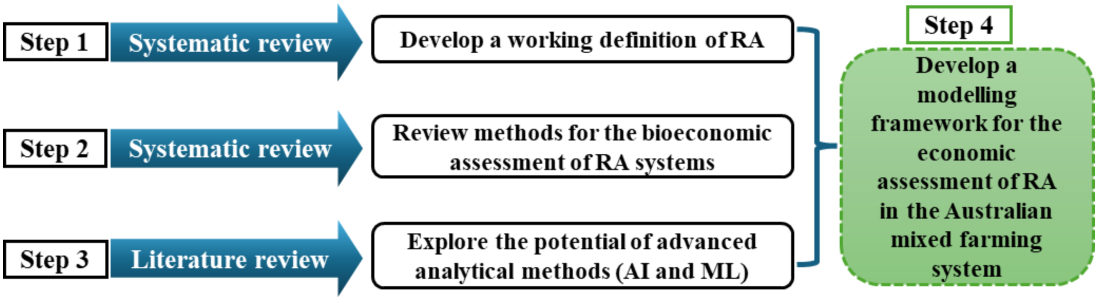

Figure 1: Overview of the main methodology followed in the study. Note: A literature review provides a broad overview of existing knowledge, while a systematic review rigorously analyses and synthesizes all available evidence related to specific research objectives.

Results

The concept of RA has garnered increasing attention in academic literature, evidenced by its frequent mention in recent studies. The top ten keywords most referenced in RA-related research include 'regenerative agriculture', 'soil health', 'biodiversity', 'agroecology', 'ecosystem service', 'sustainability', 'carbon sequestration', 'climate change', 'sustainable agriculture', and 'economy'. Despite this attention, a systematic review revealed a lack of consensus on the definition of RA. Existing definitions were categorized into three main types: principle-oriented (*n* = 10), emphasizing soil fertility, integrated pest management, and biodiversity; practices-oriented (*n* = 20), focusing on techniques such as no-till farming, cover cropping, and crop rotation to improve soil health and reduce chemical inputs; and outcome-oriented (*n* = 13), highlighting benefits such as carbon sequestration, biodiversity enhancement, community well-being, food security, and farm profitability.

Table 1. Potential indicators, tools, and models for economic RA assessment in Australian mixed broadacre agriculture.

Indicators	Tools/frameworks	Models	Advanced analytics
Production cost, product prices, gross and net farm income, return on investment, net present value, total agricultural products, cost/benefit ratio of production, equity ratio, productivity (land, input, capital, labour), crop yield, stocking rate, off-farm income, cost for fertilizer, profitability, economic stability, gross margin, return on farm asset, adoption index, machine performance, operating cash flow, operational cost, labour cost, land fragmentation, farmer's risks, average expected loss, expenditure on external inputs, conditional values-at-risk	CAPRI, FARMIS, PASMA IFSC, Multi-Criteria Decision Analysis (MCDA)	A farm management and optimization tool (Farmpredict), Farm Simulation for Sustainability Impact Assessment (FSSIM), Decision-Support Systems for Australian Grazing Enterprises (GRAZPLAN), APSIM, LUSO, MIDAS	ML algorithms: Adaptive-Neuro Fuzzy Inference Systems (ANFIS), Artificial Neural Networks (ANN), Bayesian Networks (BN), Clustering Algorithms (K-means, DBSCAN), Convolutional Neural Networks (CNN), Long Short-Term Memory (LSTM), Recurrent Neural Networks (RNN), Random Forest (RF), geographic information systems (GIS), RS

Note. The full names of some abbreviations are provided in the text.

Our study identified key indicators, tools, models, and advanced analytical methods for assessing RA in Australian broadacre farming. These include biophysical indicators such as soil health and biodiversity, key economic metrics like farm profitability (gross farm income, net farm income), production costs, productivity (land, input, capital), and risk metrics. Social aspects such as education and farmer satisfaction were also considered. Several tools and frameworks were found supportive for assessing the bioeconomic aspects of RA practices in mixed farming contexts, including the Common Agricultural Policy Regionalized Impact (CAPRI), the Farm Modelling Information System (FARMIS), the Positive Agricultural Sector Model of Austria (PASMA), and the Illinois Farm Sustainability Calculator (IFSC). The review highlighted the importance of bioeconomic models such as the Agricultural Production Systems sIMulator (APSIM), the Decision Support System for Agrotechnology Transfer (DSSAT), the Land Use Sequence Optimiser (LUSO), and the Model of an Integrated Dryland Agricultural System (MIDAS) for crop modelling and whole-farm simulations (references for the above tools and frameworks are contained in Jayasinghe et al. 2023). Additionally, advanced analytical methods such as AI, ML, big data analytics, and remote sensing (RS) were recognized for their potential to enhance bioeconomic modelling and decision-making in RA. Table 1 presents potential indicators, tools, models, and advanced analytics beneficial for economic modelling in RA. Based on these findings, a conceptual framework was developed to evaluate the bioeconomic outcomes of RA in the mixed farming settings in Australia as illustrated in Jayasinghe et al. (2023) (Figure 2).

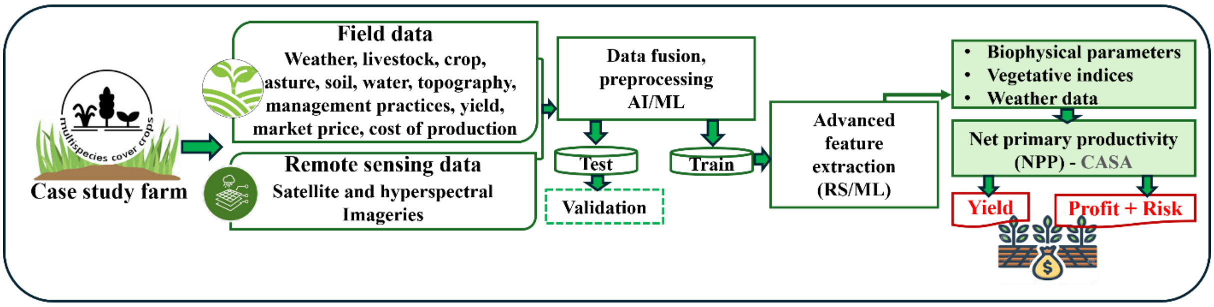

Figure 2: An integrated conceptual framework for evaluating the economic performance of RA scenarios in Australia using advanced analytics.

Discussion

The findings of this review underscore the complexity and multidimensionality of RA. After identifying gaps in existing definitions, we proposed the following working definition: "RA is an agricultural and transdisciplinary approach that integrates local and indigenous knowledge of landscapes, as well as their management, with established scientific knowledge. It combines a range of adoptable principles with context-specific practices, focusing on soil conservation as the initial step to restore soil health, enhance ecosystem functions, and promote improved socioeconomic outcomes". Our proposed definition addresses these complexities by integrating ecological, economic, and social dimensions. Emphasizing the incorporation of local knowledge with scientific principles, this definition promotes a transdisciplinary approach, supported by previous studies (Sands et al. 2023).

Assessment methods for RA include biophysical and economic indicators, tools, frameworks, models, and advanced analytics. While process-based models are commonly used to represent broadacre agriculture scenarios, they often lack spatial coverage and fail to comprehensively capture farmers' decision-making processes. To address these limitations, we propose a tailored conceptual modelling framework for evaluating RA in Australian mixed farming systems (Jayasinghe et al. 2023). This framework integrates bioeconomic indicators, tools, frameworks, models, and AI/ML-driven techniques, thereby enhancing relevance and standardizing RA economic assessments. Incorporating local and indigenous knowledge through participatory research approaches assists the effective implementation and assessment of RA.

Implementing this framework faces several challenges. The effects of RA on soil health, crop/livestock productivity, and yields are likely to be long term. Therefore, extended data collection timelines are required which constraints the timely delivery of comprehensive data. Limited access to standardized data further impedes comprehensive assessments, exacerbated by RA's context-specific nature, which demands tailored approaches for diverse agricultural contexts. While sophisticated experimental designs are essential for capturing the complexities of RA, their absence limits precise data collection, identification of causal relationships, and restricts the validation and refinement of the proposed framework. To address these challenges, studying commercial farms practicing context-specific RA methods provides real-world insights into environmental and socio-economic impacts. Complex RA interventions, such as multispecies cropping, pose challenges for accurate simulation using biophysical models like APSIM, necessitating the integration of RS and ML technologies for precise and scalable RA assessments. To address the absence of an effective control treatment, historical data and baseline scenarios can be used, while RS and ML help identify patterns that serve as proxies for controls. This approach, exemplified in Figure 2, employs field and RS data to calculate parameters such as net primary production (NPP) using the Carnegie-Ames-Stanford Approach (CASA). NPP represents the net carbon assimilated through photosynthesis (Rodigheri et al. 2024). Integrating NPP into our modelling framework provides essential insights into ecosystem functioning and enables effective assessment of the impacts of RA practices on yield and profitability. Integrating AI and ML with RS overcomes limitations of traditional models, leveraging extensive datasets to uncover comprehensive insights into RA's economic impacts (McLennon et al. 2021). This method also demonstrates effective modelling of complex farming systems. using RS data, supporting standardized RA assessments globally but requiring robust data infrastructure and specialized expertise.

Conclusion

The review underscores the importance of establishing a standardized definition and robust assessment methodologies for RA. By consolidating various assessment tools and defining RA across different contexts, including Australia, the study emphasizes the necessity for ongoing dialogue and collaboration among stakeholders. The proposed working definition integrates ecological, economic, and social dimensions, emphasizing the fusion of local knowledge with scientific principles through transdisciplinary approaches. The conceptual framework by Jayasinghe et al. (2023) for evaluating RA in mixed farming systems exemplifies the integration of diverse indicators, tools, and bioeconomic models. However, the implementation of such frameworks faces challenges related to data availability and methodological complexity. Specifically, bioeconomic models alone are insufficient for simulating complex RA scenarios. Integrating advanced technologies such as RS and ML is essential to overcome these challenges. This approach focuses on estimating NPP, yield, and profitability, supporting standardized assessments globally, particularly in modelling complex RA practices like multispecies cropping. Due to the complexities in evaluating RA practices, overall analysis should use several independent steps that are drawn together within the common framework. Continuously refining these modelling frameworks and assessment methods is vital to ensure robust and reliable outcomes. This modelling work would contribute to evidence-based decision-making and promotes the wider adoption of RA.

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