



## Quantifying ecosystem services: A conceptual framework for regenerative agriculture in Western Australia's rangelands

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**Key words:** Ecosystem services; net primary productivity; remote sensing; machine learning; InVEST model

### Abstract

Rangelands and pastoral systems play vital roles in biodiversity conservation, carbon sequestration, and supporting livelihoods. However, their vast and heterogeneous landscapes pose significant challenges for assessing and managing ecosystem services (ES). This study aimed to develop a comprehensive framework to quantify the impacts of regenerative agriculture (RA) practices within these ecosystems, focusing specifically on Western Australia's rangelands. These practices offer a sustainable approach to enhancing ecosystem resilience, yet their effects on ES remain underexplored. The framework integrates the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model, remote sensing technologies such as high-resolution satellite imagery, and machine learning (ML) techniques. These methodologies systematically map and assess key ecosystem services across different spatial scales, including provisioning (e.g., net primary productivity (NPP)), regulating (e.g., water dynamics), cultural (e.g., habitat quality), and supporting services (e.g., soil health). Using field and climate data from 2000 to 2023, along with satellite indices (NDVI, LAI), were used to calculate Photosynthetically Active Radiation (PAR) and Fraction of PAR Absorbed (FPAR), which are crucial for estimating Net Primary Productivity (NPP). Advanced ML algorithms, including Random Forest and Neural Networks, are employed to predict key ecosystem services. The framework supports the simulation, evaluation, and optimization of regenerative agriculture practices, thereby enhancing ecosystem resilience and promoting sustainable rangeland resource management. Forecasting ecosystem values in monetary terms, especially under regenerative agriculture scenarios, equips policymakers with tools to assess policy outcomes and advance sustainable land management in rangelands and pastoral systems. Despite its capabilities, persistent challenges such as data availability, the nuanced and context-specific nature of regenerative agriculture scenarios, and ethical considerations—such as community involvement in data collection—are critical for successfully implementing the framework.

### Introduction

Rangelands, which cover approximately 40% of Earth's terrestrial surface, provide essential ecosystem services (ES), including biodiversity conservation, carbon sequestration, water regulation, food, and livelihood support for an estimated 200–500 million pastoralists worldwide (Alkemade et al. 2013; Maestre

et al. 2022). In Australia, these vast arid and semi-arid landscapes support Indigenous communities, livestock grazing, and industries such as mining and tourism. However, rangeland ecosystems are increasingly threatened by overgrazing, invasive species, soil erosion, and climate variability, resulting in significant degradation (Gemetchu and Dalle 2023). For example, 44% of grazing lands in northern Australia show signs of degradation, which compromise their ecological and economic functions, including the capacity to sustain biodiversity, store carbon, and maintain soil and water quality (Nielsen et al. 2020).

Regenerative agriculture (RA) presents a promising solution for restoring degraded rangelands (Khangura et al. 2023). Practices such as rotational grazing, greater tactical adjustment of carrying capacity (e.g. livestock sales, use of irrigated pasture systems), and landscape rehydration aim to restore soil health, improve water retention, and enhance biodiversity by fostering more diverse and resilient ecological systems (Jayasinghe et al. 2023; Lal 2020). However, assessing the impacts of RA on ES—such as carbon sequestration, biodiversity enhancement, and water retention—is complex due to the spatial and temporal variability inherent in rangeland ecosystems. Traditional assessment methods, including low-resolution remote sensing and qualitative surveys, lack the precision and scalability needed for effective evaluation (Kabir et al. 2020).

This study aimed to develop a conceptual modelling framework that integrates remote sensing (RS), Geographic Information Systems (GIS), and machine learning (ML), to assess the impacts of RA practices on ecosystem services in Western Australia's rangelands. By incorporating models such as Carnegie-Ames-Stanford Approach (CASA) and Integrated Valuation of Ecosystem Services and Trade-offs (InVEST), the framework facilitates precise, scalable, and localized assessments of ecosystem services. This approach provides detailed spatial and temporal data tailored to the unique conditions of rangeland ecosystems, addressing critical gaps in current methodologies. Ultimately, this research will offer actionable insights for sustainable rangeland management, enabling land managers and policymakers to make informed decisions that promote the long-term ecological and economic sustainability of rangelands.

## Methods

A literature review identified key ES relevant to rangelands, such as soil organic carbon (SOC), water retention, and biodiversity, which were selected for their ecological and practical significance (Mashizi et al. 2019). These ES were chosen to assess the effects of RA practices, including rotational grazing, tactical stocking adjustments, landscape rehydration, and soil management (Jordon et al. 2022). Western Australia's rangelands were selected for their ecological importance, challenges related to land degradation, and representation of arid and semi-arid climates, enhancing the broader applicability of the framework. The framework applies RS, GIS, ML algorithms, and biophysical models to assess ES and link them to RA practices:

***Ecosystem services assessment:*** High-resolution satellite indices (e.g., NDVI, LAI), combined with field data (e.g., soil properties, vegetation biomass), are used to monitor spatial and temporal variations in key ES indicators. The CASA model estimates Net Primary Productivity (NPP) to quantify vegetation growth and carbon fluxes. The InVEST model, in conjunction with ML algorithms, assesses carbon sequestration, water retention, biodiversity, and soil health. ML algorithms, and biophysical models (e.g., CASA, InVEST). All datasets are., RS data from Sentinel-2 and MODIS, harmonized for spatial and temporal consistency, serve as the foundation for ES mapping across rangelands.

***Linking RA to ecosystem services:*** The effects of RA practices, such as rotational grazing and landscape rehydration, on ES are quantified using GIS and biophysical models. Changes in SOC, soil health, and water retention resulting from RA practices are mapped and analysed.

**Model validation:** Model outputs are compared with field-measured data (e.g., vegetation biomass, SOC), while uncertainty is assessed using Monte Carlo simulations and sensitivity analysis. This iterative process ensures robustness and adaptability to varying management practices and climatic conditions.

## **Results**

The conceptual framework was developed to quantify key ES and assess the impact of RA practices on Western Australia's rangelands (Figure 1). The case study region will be selected based on its ecological significance and the ongoing implementation of RA practices. This approach highlights how RA practices, such as rotational grazing and landscape rehydration, contribute to the enhancement of ES and the resilience of ecosystems. The framework is currently in the conceptual stage, with full implementation planned for future studies.

### ***Ecosystem service quantification***

Carbon sequestration is estimated through both aboveground and belowground biomass, with NPP serving as the basis for SOC estimation (Lal 2004). RA practices, like rotational grazing, are expected to improve carbon storage by increasing SOC. Water retention is evaluated using a soil water balance model, integrating InVEST-driven evapotranspiration and water availability (Su et al. 2020). Improved soil health through RA practices like soil rehydration enhances water retention, which contributes to ecosystem resilience. Biodiversity is assessed using diversity indices (e.g., Shannon and Simpson), which are linked to NPP and floral density (Pla et al. 2011). RA practices are anticipated to increase biodiversity by promoting diverse plant communities. Soil health is evaluated by measuring soil organic matter, nutrient cycling, and improvements in soil structure (Doran et al. 1994). Soil health is a key indicator of RA's success in promoting sustainable land management. Soil erosion is modelled using the Revised Universal Soil Loss Equation (RUSLE) (Renard 1995), while pollinator activity is inferred from NPP-driven floral density (Tylianakis et al. 2008). Greenhouse gas (GHG) mitigation is quantified by CO<sub>2</sub> sequestration and reductions in CH<sub>4</sub> and N<sub>2</sub>O emissions (Joyce et al. 2013). GHG mitigation is enhanced by RA practices that improve carbon sequestration and reduce emissions from soil disturbance.

### ***Visualization and trend analysis***

The InVEST model and ML algorithms, including Random Forest (RF) and Convolutional Neural Networks (CNN), are employed to upscale ES metrics across larger spatial and temporal scales. High-resolution satellite imagery, in conjunction with field surveys, improves the accuracy of predictions and captures spatial heterogeneity (Burke et al. 2021). Tools such as Google Earth Engine and ArcGIS are used for spatial mapping and trend analysis to evaluate seasonal and long-term ES dynamics under varying climatic conditions.

### ***Current status and future work***

While still in the conceptual phase, the framework is designed to enable the spatial and temporal mapping of ES, allowing for future scenario evaluations and sensitivity analysis.

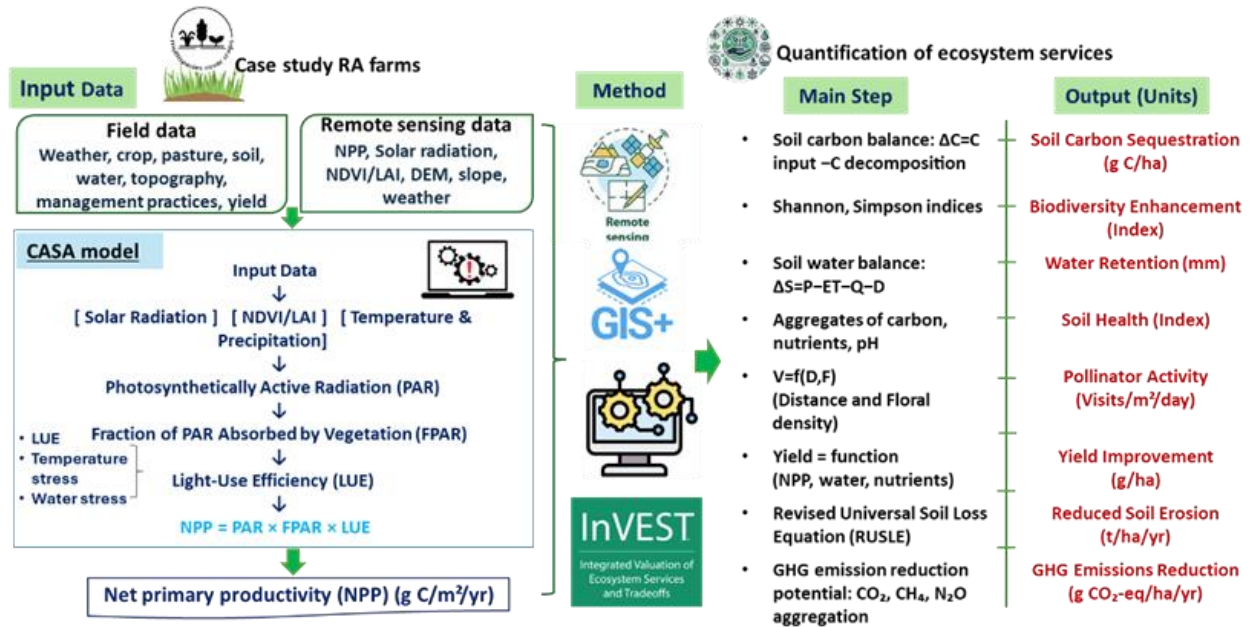


Figure 1. Conceptual framework for evaluating ecosystem services of regenerative agriculture in rangeland systems

### Discussion

This study proposed a novel framework for assessing the impact of RA on ES in Australia's rangelands. By integrating RS, biophysical models, and ML, the framework enhances precision compared to traditional methods by accounting for regional variability and enabling scalability across landscapes (Kabir et al. 2020).

The selected ES—SOC, water retention, and biodiversity—are essential for ecological stability and effective land management. SOC plays a critical role in soil fertility and climate mitigation, while water retention contributes to climate resilience. Biodiversity, assessed through diversity indices, supports habitat quality and pollinator populations, both of which are vital in rangeland ecosystems (Lal 2004; Su et al. 2020; Pla et al. 2011). Previous studies (e.g., O'donoghue et al. 2022; Jayasinghe et al. 2023) confirm the relevance and quantification potential of these services in RA systems, providing a strong basis for their inclusion in this framework. The framework directly informs RA decision-making by quantifying the impact of interventions on key ES. For example, rotational grazing can be evaluated for its effect on SOC and biodiversity through changes in NPP and species diversity indices. Tactical adjustments to carrying capacity, such as managing stocking rates or utilizing irrigated pastures, can be assessed for their influence on water retention and carbon storage across varying climatic and land-use scenarios. Landscape rehydration practices can also be linked to water retention improvements via soil moisture dynamics analysis from high-resolution remote sensing data.

The framework employs NPP to quantify carbon sequestration and link it to broader ecological processes. The CASA model estimates NPP using satellite and field data, providing regional estimates and addressing local variability (Zhu et al. 2017). This allows for region-specific customization, improving ES prediction accuracy by accounting for local environmental and land-use variability. The integration of ML algorithms, such as RF and CNNs, enhances the model's ability to capture complex, non-linear relationships, addressing landscape heterogeneity. These techniques have proven effective in ecological monitoring (Liu et al. 2018).

By integrating these tools, the framework helps land managers prioritize RA interventions based on their benefits and trade-offs, maximizing ES outcomes while considering landscape variability and resource availability. It can guide decisions on rotational grazing, soil health, and water retention strategies tailored to local conditions.

While the framework offers significant advantages, challenges remain, particularly regarding data quality and model uncertainty. Reliable field data is critical for model calibration, while uncertainty analysis—incorporating sensitivity and Monte Carlo simulations—addresses potential sources of error (McFarland et al. 2008). Successful implementation of the framework also hinges on collaboration with land managers and policymakers to ensure its practical applicability across diverse rangeland ecosystems. Despite these challenges, the integration of high-resolution data, advanced modelling techniques, and stakeholder engagement positions this framework a powerful tool for sustainable land management. It provides a solid foundation for evaluating RA interventions and enhancing ecosystem services in rangeland environments, offering valuable insights for land managers and policymakers.

### Conclusion

This study proposed a comprehensive framework to assess the impact of RA on multiple ES in Western Australia's rangelands, including SOC, water retention, biodiversity, soil health, soil erosion, and pollinator activity. The framework integrates RS, biophysical models (CASA, InVEST), and ML techniques to quantify these services with high precision and scalability. It uses NPP as a key input in the InVEST model to estimate other ES. Despite challenges related to data quality, model calibration, and uncertainty, the framework provides valuable tools for optimizing RA practices, supporting sustainable rangeland management, and enhancing ecosystem resilience.

### Acknowledgements

This research was supported by the Winangay Early Research Career (CERC) scholarship.

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