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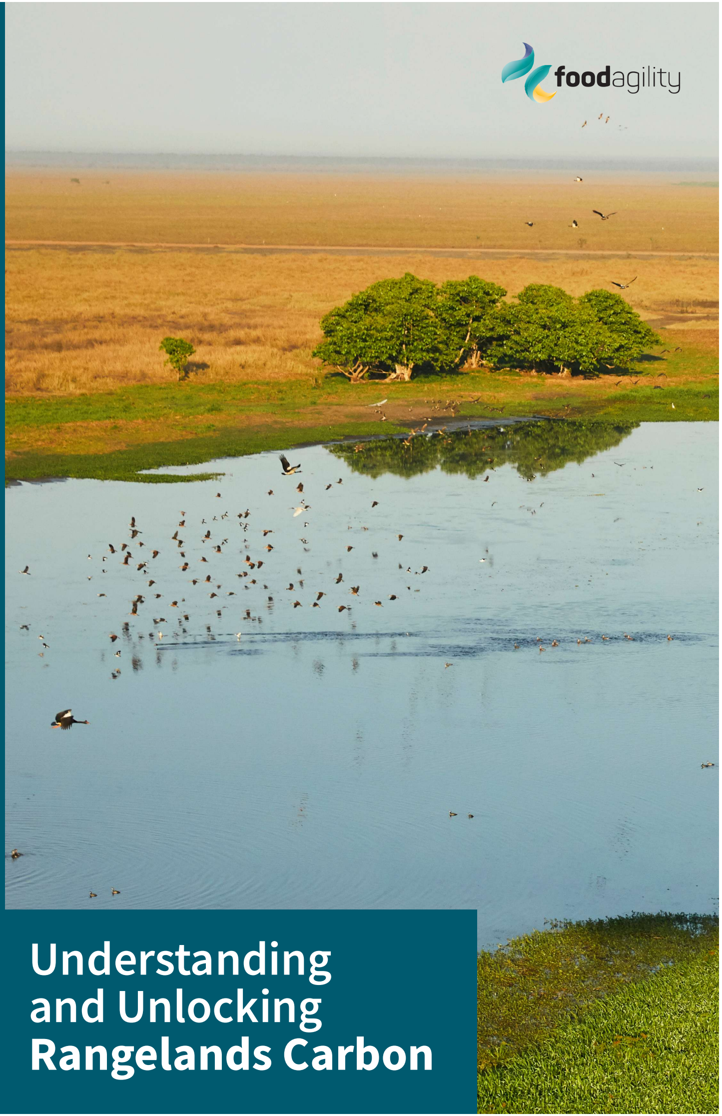

Understanding and Unlocking Rangelands Carbon

ISBN: 978-1-7638178-9-0
Project Name: Rangelands Carbon
Project No: FA110

Citation: Understanding and Unlocking Rangelands Carbon, Food Agility CRC
Cover: Image supplied by AACo
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Electronically published by Food Agility CRC at www.foodagility.com in January 2026.
The Food Agility CRC is funded under the Australian Government Cooperative Research Centres Program.

Contents

Glossary of Acronyms

AACo	Australian Agricultural Company
DGG	Data Governance Group
DMP	Data Management Plan
FAIR	Findable, Accessible, Interoperable, Reusable
LC	Land Condition
LRU	Landscape Response Unit
MAPE	Mean Absolute Percentage Error
MLP	Multilayer Perceptron
SOC	Soil Organic Carbon
TSDM	Total Standing Dry Matter
VRD	Victoria River District

Executive Summary

This project represents the most comprehensive investigation into Australian rangelands soil carbon to date, aiming to support sustainable land management and pave the way for participation in the carbon market.

Livestock producers and land managers are increasingly focused on managing landscape carbon, not just to boost profitability and productivity, but also to improve sustainability, build resilience, meet carbon targets and respond to market expectations.

Measuring soil and vegetation carbon across vast rangelands is both expensive and time consuming, and even when the data is available, reliably estimating the carbon sequestration potential and the best management strategies across complex rangelands landscapes can be challenging.

This project aimed to develop an accurate and affordable method for estimating carbon in Australian rangelands and assessing how different land management techniques influenced soil carbon. This supports holistic land management and participation in the carbon market.

Using advanced analytics, including machine learning and process modelling, the research identified a statistically significant relationship: better land condition tends to have higher Soil Organic Carbon (SOC), creating a strong incentive for sustainable land management practices.

The project delivered practical outputs that strengthen decision-making and monitoring capabilities. A high-resolution SOC baseline map was developed alongside an advanced digital Integrated Model, providing a robust foundation for modelling and scenario analysis. These tools enable more accurate assessments of carbon dynamics across diverse rangeland environments.

Research examining the sampling density required for SOC quantification in these environments showed that accurate results could be achieved at much lower sampling rates than was previously thought, reducing field sampling costs.

In addition, a natural capital risk platform was created to systematically evaluate nature-related impacts and dependencies associated with SOC. This platform visualises spatial risk patterns and demonstrates their implications through a fire case study, offering a clear view of how environmental risks intersect with carbon strategies.

> For us, this project opens up significant opportunities across our landscape not just in potential carbon sequestration and market access but also supporting nature more broadly. It has given a holistic view of our landscape assets and how our management decisions affect those assets. Another notable outcome is the diverse connections within the project team and the expertise and insights they've offered that we've been able to apply across our sustainability program.
>
> **Naomi Wilson, Head of Environment and Sustainability, AACo**

foodagility | AACo | cibolabs | FLINTpro
UTS | carbonlink | Charles Sturt University | Federation University

Budget:

$6.6M cash

$188M in-kind

Duration:

3 years

Team:

8 partner organisations

50+ team members

UTS, foodagility, FLINTpro, Federation University, AACo, carbonlink, Charles Sturt University, cibolabs

The Rangelands Carbon project team visited AACo's La Belle Downs Station in the Northern Territory in October 2022.

Data Collection & Management

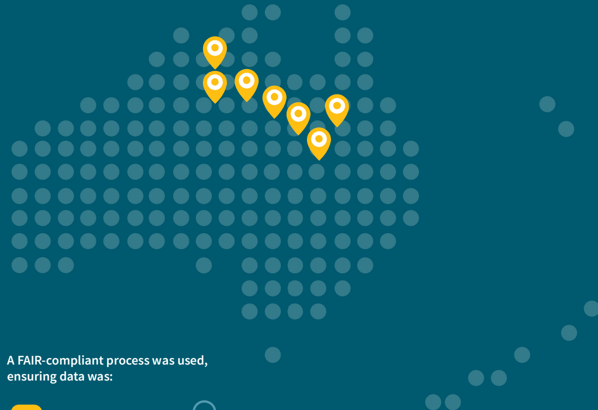
2,257
cores, each up to 1.2 metres deep

1.97km
total core length

40,427
sublayers analysed

>100
covariates

>20TB
data



A FAIR-compliant process was used, ensuring data was:

- **F** FINDABLE
- **A** ACCESSIBLE
- **I** INTEROPERABLE
- **R** REUSABLE

Key Outcomes

Data collection and integration

- Australia's largest rangelands soil carbon sampling: 2,257 soil cores (40,427 sublayers, >30 properties, 106 covariates) from 908 sites, generating 20TB of data.
- Integrated new field, partner and public data with remote sensing (drone, satellite) and advanced analytics.
- Data managed under a comprehensive FAIR (Findable, Accessible, Interoperable, Reusable) framework, with robust governance and sharing protocols.

Landscape segmentation and stratification

- Developed a novel Landscape Response Unit (LRU) approach to stratify the properties for experimental design and sampling. This involved segmenting the landscape into ecologically meaningful units using hierarchical clustering of remote sensing, geomorphology and climate data.
- Linked LRUs with measured landscape condition (measure from A-D of the health and productive capacity of grazing land) demonstrating that both the type of landscape (as defined by LRUs) and its condition are key, independent predictors of soil organic carbon.
- This dual approach pinpoints where management will most impact carbon stocks and supports scaling across diverse rangelands.

Key scientific findings

- Statistically significant, though noisy, positive relationship between land condition and SOC: each class improvement in land condition increases SOC by 0.65 t C/ha on average.
- Ungrazed areas had 1.49 t C/ha higher SOC than adjacent grazed areas.
- Land condition is a practical, scalable indicator for carbon and land management.

Advanced modelling and analytics

- Built an advanced, multi-model analytics platform (the Integrated Model) combining process models (RothC, FullCAM), machine learning (MLP, Random Forest, SVR) and spatial data to estimate and predict carbon in an equivalent soil mass of 3500 t/ha under different management and climate scenarios.
- Model calibration showed best performance with site-specific empirical data; spatial data alone introduces bias, especially in under-sampled regions.

Management and carbon market relevance

- Demonstrated that management changes (e.g., improving land condition) could increase SOC, supporting carbon credit generation under the Australian Carbon Credit Unit (ACCU) scheme.
- Even small local SOC changes, when scaled, can deliver significant carbon sequestration at the enterprise or regional level.
- The Integrated Model supports carbon budgeting, insetting and monetisation opportunities.

Sampling optimisation

- Identified that low sampling densities (500 ha/core) can be as effective as intensive sampling in homogeneous landscapes, potentially reducing project costs.

Natural capital and risk assessment

- Treated soil carbon as natural capital, systematically assessing both risks to SOC (e.g., temperature, fire, climate change) and risks to nature from management interventions (e.g., reduced stocking rates).
- Developed a data integration platform to monitor and map nature-related risks, including a fire risk demonstration tool.

Social learning and collaboration

- Over 50 team members from eight partner organisations, with new approaches to engagement, knowledge sharing and cross-disciplinary learning.
- Created enduring networks of trusted colleagues and mentors and embedded adaptive, strengths-based project management.

The Integrated Model

Advancing Carbon Management in Australia's Rangelands

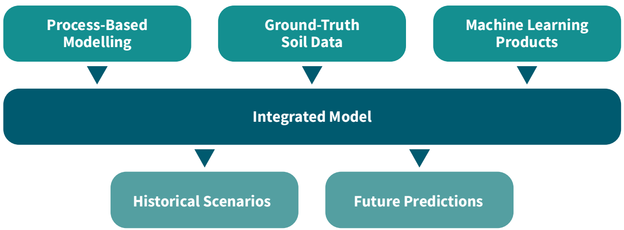
This project delivered a suite of innovative digital tools, shifting carbon estimation from expensive on-ground physical measurement to sophisticated, scalable and predictive modelling.

At the core is the **Integrated Model**, which represents a major advancement in the science and practice of carbon management across Australia's rangelands.

It is a comprehensive, spatially explicit digital platform that integrates soil, pasture and woody vegetation carbon models with both field and remote sensing data. This combination provides robust, actionable insights into carbon stocks and their dynamics, enabling informed decision-making for sustainable land management.

The model equips land managers, policy makers and industry stakeholders with a powerful tool for evidence-based carbon management. It estimates current and historical carbon stocks, projects future changes under different management and climate scenarios, and identifies strategies for optimising carbon sequestration and sustainable land use. It also supports climate reporting and participation in carbon markets, making it highly relevant for both operational and strategic planning.

Its development marks a step change in the ability to manage carbon as a natural capital asset. By making quantification more affordable, reliable and accessible, the Integrated Model sets a benchmark for future carbon management initiatives in Australia and beyond. Its rigorous scientific foundation and adaptability position it as a transformative platform for scaling sustainable practices across diverse landscapes.



This project is the **first in Australia's rangelands** to show a statistically significant link between land condition and soil carbon highlighting how **management practice can influence carbon sequestration** and **landscape resilience**.

The Integrated Model offers a **scalable and cost-effective solution** for carbon accounting and **sustainable land management**.

The Integrated Model allows users to:

1 **Assess historical carbon change across land holdings**

2 **Model future carbon scenarios under different climate and management regimes**

3 **Identify high opportunity areas for carbon sequestration based on current carbon levels and storage potential**

By making carbon quantification both **affordable** and **scientifically robust**, this project empowers land managers with a clear pathway to **sustainably manage their landscapes and participate in the carbon economy**.

Key benefits include:

Carbon credit eligibility

Precise soil carbon measurements support project scoping under the ACCU scheme, unlocking financial incentives.

Insetting and emissions reporting

Verified carbon sequestration can be reported and used to offset emissions within supply chains or operations.

Targeted land management

Data-driven insights help identify high potential areas for carbon capture and guide strategic interventions to improve landscape health.

Enhanced sustainability credentials

Transparent reporting strengthens environmental reputation and supports ESG goals.

Landscape health diagnostics

The system highlights ecological priorities, enabling proactive and informed stewardship.

Scalable national framework

The model is adaptable across diverse Australian landscapes, supporting national SOC accounting.

The sampling program and SOC model

The project delivered the most comprehensive soil carbon dataset ever assembled for northern Australian rangelands, forming the foundation for the region's most detailed soil carbon estimation model to date.

Over three years, the team collected 2,257 soil cores, each up to 1.2 metres deep, from 908 sites across 6 million hectares of AACo's Barkly, Victoria River District (VRD) and Gulf properties. This produced more than 40,000 sublayers and considered >100 covariates and generated >20TB of data.

The integrated dataset and spatial SOC model enable land managers to identify areas with the greatest potential for carbon sequestration and design targeted interventions.

This work sets a new benchmark for soil carbon assessment in northern Australian rangelands and underpins scalable, cost-effective carbon projects.

Sampling and analysis

The sampling strategy was meticulously designed to generate high-quality, representative data. A novel stratification approach using Landscape Response Units (LRUs) grouped ecologically similar segments based on remote sensing, geomorphology and climate data, enabling precise, scalable sampling and targeted assessment of management impacts.

The design included paired sites across fence lines to assess grazing impacts, as well as longitudinal and historically sampled sites to track changes over time.

Soil samples were analysed using traditional laboratory methods and advanced technologies such as Soil Condition Analyses System and spectroscopy, with machine learning models predicting soil properties including SOC.

Digital mapping and modelling

The Rangelands Carbon team applied state-of-the-art digital soil mapping and machine learning techniques to create spatially explicit, high-resolution SOC maps. Multiple models were trialled including Linear Regression, Random Forest, Support Vector Regression and Multi-Layer Perceptron (MLP) using extensive field data and over >100 environmental covariates such as climate, terrain and satellite-derived indices.

Spatial precision

The model delivers detailed, spatially explicit estimates of carbon stocks and changes, enabling users to visualise carbon distribution and trends at property, regional and landscape scales.

Scenario analysis

The model allows users to simulate the impact of various land management strategies and climate scenarios on carbon stocks, supporting both operational and strategic planning.

Scientific rigor

Calibration and validation were conducted using independent datasets, ensuring the reliability and credibility of model outputs.

Demonstrated relationship between land condition and soil carbon

The sampling program revealed a statistically significant positive relationship between SOC and land condition, with an average increase of 0.65 tonnes of carbon per hectare for each class of land condition improvement.

Carbon market participation

The model's outputs can help landholders assess the potential of carbon projects under the ACCU Scheme by delivering cost-effective estimates of SOC change. Because the model was built for a specific study area, it requires validation in other regions before its results can be confidently applied to them.

Adaptability

The model's framework is designed for broader application across Australia's rangelands, with the capacity for local calibration and extension.

An MLP model was selected for its robustness and ability to capture complex, non-linear relationships even with limited training samples. This calibrated SOC model supported carbon project design, stratification and baseline estimation, and was a critical input to the project's Integrated Model.

The Rangelands Carbon project team had a capacity building session to better understand the complexity of soil and pasture.

Pasture carbon

Cibo Labs' pasture biomass estimation model was tailored with project data, using over 6,000 field pasture cuts and Sentinel-2 satellite imagery to estimate Total Standing Dry Matter (TSDM) as a proxy for pasture carbon. This output was a key input to the Integrated Model.

The model employs a three-layer MLP regression, trained on both field and satellite data, and incorporates regularisation and robust loss functions to ensure accuracy and stability.

Field data was collected using a dedicated mobile app, with samples taken across diverse sites and conditions, and validated through rigorous cross-validation and error analysis.

The model achieved high accuracy, with a mean absolute percentage error (MAPE) of approximately 30% for pasture cuts, aligning with the inherent variability in field data.

TSDM estimates are available at high spatial and temporal resolution, supporting both property-level and paddock-level management decisions.

Woody carbon

The project delivered a considerable advance in quantifying woody vegetation carbon across Australia's rangelands (for ingestion by the Integrated Model) by integrating machine learning, remote sensing and field data.

The 'Woody Model', developed by the University of Technology Sydney, combines Sentinel-2 satellite imagery, high-resolution aerial photography and digital surface/elevation models to estimate woody cover density and height at scale.

Advanced machine learning algorithms, including Random Forest and XGBoost, were trained and validated using field plot data and digital surface models.

Deep learning frameworks (such as Detectron2) were used for precise segmentation of woody cover boundaries, overcoming the challenge of detecting scattered, low-density trees in rangelands.

The model achieved high predictive accuracy, with Random Forest delivering the best performance (MSE = 0.008, R^2 = 0.51), and enabled the creation of 0.5m woody cover maps and 10m cover density estimates.

Temporal analysis revealed spatial and seasonal variations in woody density across AACo properties, providing valuable insights for land management and carbon accounting.

Data Management

The project established a robust, collaborative data management framework to ensure the integrity, security and usability of over 20 terabytes of complex, multi-partner research data.

This framework was designed to support the FAIR data principles - Findable, Accessible, Interoperable and Reusable - while respecting confidentiality and intellectual property requirements.

A comprehensive Data Management Plan (DMP) was co-designed and implemented, covering the entire data lifecycle from capture to archiving. This included standardised protocols for data creation, storage, organisation, sharing, retention and disposal.

A cross-partner Data Governance Group (DGG) was established to oversee data management decisions, resolve issues and ensure consistent practices across all project partners.

Data was systematically collected, standardised and shared across multiple platforms, including SharePoint and Azure cloud infrastructure, with a unique site identifier system enabling reliable linkage of soil, pasture and UAV datasets.

The data management approach enabled seamless collaboration, efficient data analysis and ensured that research outputs remain accessible and reusable for future initiatives.

Natural Capital Risk

The project developed a novel and valuable approach to understanding and managing natural capital risks associated with SOC sequestration in rangelands.

It assessed the risks and opportunities linked to SOC sequestration and storage across rangelands, clarified which risks are most significant, identified useful indicators and data sources, and demonstrated how environmental data can support better decision-making.

This workstream, led by Federation University, complemented the project's carbon modelling by systematically identifying, assessing and visualising environmental risks that could affect SOC storage.

A structured materiality assessment was conducted to identify nature-related risks to SOC, as well as risks arising from changes in land management practices.

The assessment followed international risk management standards, focusing on both 'dependency risks' (factors that affect the ability of soils to sequester carbon, such as water availability, temperature, fire, soil quality and pests) and 'impact risks' (potential negative effects across five management actions like irrigation, pasture improvement or controlled burning).

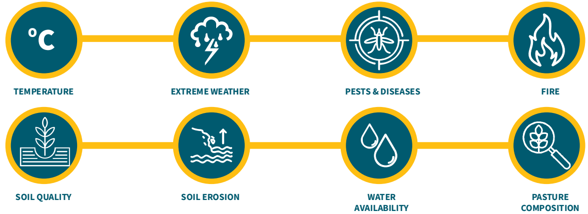
Eight major dependency risks and ten impact risks affecting soil carbon in rangelands were identified. Most were assessed as potentially high or very high, albeit, with high uncertainty in some areas.

The team developed the NatureRisk online platform, a spatial decision-support tool that integrates soil carbon data with indicators such as fuel load and ignition risk, enabling targeted assessment and visualisation of fire risk to SOC.

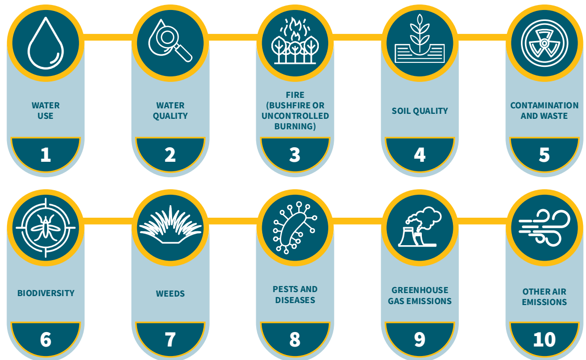
A key finding was that rising temperatures due to climate change pose very high risk to SOC storage.

Key Steps

This project systematically assessed risks to SOC in Australian rangelands. Eight key environmental dependency risks were identified, most rated high or very high risk, though risk varies by location and management.



Ten major impact risks were also identified. These are the negative effects that land management changes can have on the environment.



Five management scenarios were assessed for their influence on these impact risks:

Management change can increase both downside risk and upside potential. The associated trade-offs therefore need to be clearly identified and carefully considered.

Nature aligned practices such as lighter grazing pose minimal environmental risk, maintaining ecosystem integrity whilst supporting carbon gains. In contrast, intensive interventions like large-scale irrigation may accelerate carbon sequestration but risk degrading natural capital. This highlights the need for careful planning and integrated risk management to balance carbon benefits and environmental consequences.

Recommendations for future research

This project identified a range of opportunities to leverage and extend the research outcomes.

Quantify SOC change rates by land condition class over time using fixed long-term monitoring sites.

Extend SOC measurement and modelling to capture full soil core sample beyond 30cm to understand depth profiles, stability and creditable carbon.

Refine and validate the integrated modelling framework (RothC + ML + remote sensing) on additional properties and regions, including independent validation datasets.

Investigate the effects of nutrients and legumes (N, P, K, S, species mix) on SOC dynamics under realistic grazing management.

Improve remote sensing methods for land condition and biomass, comparing satellite, UAV and LiDAR methods for cost–accuracy trade-offs.

Develop robust woody carbon models that combine plots, LiDAR, SAR and optical imagery for structure, growth and mortality in rangelands.

Quantify the impact of fire regimes, drought and grazing pressure on SOC and woody carbon to parameterise risk in models and methods.

Explore natural capital risk metrics that link SOC, pasture condition, biodiversity and financial risk in one modelling framework.

Test reduced sampling intensities and stratification rules across different rangeland types to define where low sampling densities can be used for SOC quantification without compromising accuracy.

Evaluate ACCU method design (Schedule 1 vs Schedule 2) using simulation studies to test crediting thresholds, uncertainty and permanence assumptions under rangeland conditions.

Develop longitudinal data set for model validation by remeasuring SOC at sites through time.

Team Members

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Daniel	Chapman	AACo
Edward	Gubbins	AACo
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Andrew	Gatenby	CarbonLink
Chioma	Igwenagu	CarbonLink
Sushil	Lamichhane	CarbonLink
David	Manning	CarbonLink
Chris	McCosker	CarbonLink
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Tony	Gill	Cibo Labs
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