Modelling SOC change: the role of climate, soil, land-management, and carbon input in Australian farming systems

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Abstract: Soil organic carbon (SOC) is a key terrestrial carbon sink, vital for ecosystem functioning and climate resilience. Increasing SOC through land management practices such as crop rotation, reduced tillage stubble management and optimized grazing is central to nature-based solutions that support both productivity and long-term sustainability. However, monitoring SOC change and identifying its drivers remain challenging due to uncertainties in carbon input estimates and limited data on land management practices—making it difficult to distinguish changes driven by management from those resulting from inherent spatial and temporal variability across regions and farming systems. Using a national soil organic carbon monitoring dataset collated across 308 representative Australian paddocks with over a decade of paddock scale land management records, we (i) applied a multi-model ensemble to improve estimates of carbon inputs, and (ii) used a range of statistical approaches to disentangle the relative influence of climate, soil, and management on SOC dynamics.

We estimated paddock-level crop yields from 2010 to 2023 using a multi-model ensemble combining APSIM (Holzworth et al., 2018), CERES-EGC (Gabrielle et al., 2006), and an empirical rainfall-yield model (Australian National Greenhouse Accounts, 2024). We improved yield estimates by averaging predictions from the three models and validating them with over 1200 farm observations, which were then used to calculate annual carbon inputs based on crop-specific factors (allocations and C contents of the components) and stubble management options. Using carbon input estimates from our multi-model approach, we assessed the influence of management history, soil attributes, and climate on SOC changes by quantifying management intensity (e.g., stubble management, tillage, crop types, fertilisation, and rotation diversity) and integrating it with corresponding soil and climate data. A two-step modelling process—Random Forests for variable selection, and Generalised Additive Models (GAMs) for interpretability—highlighted how long-term practices and climate jointly drive SOC dynamics across land uses, improving our understanding of carbon stock changes.

Each of the three models—APSIM, CERES-EGC, and the empirical model—captured different aspects of crop growth, with varying accuracy and complexity. While the empirical model showed the highest predictive accuracy overall (R2 = 0.39 and RMSE = 1.74 t biomass ha-1), APSIM best captured long-term yield trends. To improve robustness, we combined all three models into an ensemble, which reduced individual model biases and structural uncertainty, achieving an R2 = 0.49 and an RMSE = 1.42 t biomass ha-1. Building on the ensemble yield modelling and management history analysis, we explored how pedo-climate and management variables relate to changes in SOC. Across all sites, mean carbon input, rainfall, temperature, clay, and baseline SOC consistently emerged as the strongest predictors of SOC change. The GAM results show that higher rainfall (>800 mm y-1) and clay content (>20%) are positively associated with SOC gains, while elevated average temperatures (>17 °C) and high baseline SOC constrain further increases, indicating possible saturation. Among management practices, perennial and annual grasses and stubble grazing were linked to SOC increases, whereas intensive tillage was associated with SOC losses— though uncertainty was higher for this category due to the limited number of sites with consecutive tillage. Nitrogen fertiliser application showed a weak but slightly positive relationship with SOC variation, plateauing at higher rates. Crop rotation diversity appeared to have a minimal effect overall, with limited evidence of SOC response across land uses.

Our findings demonstrate that while land management practices can influence SOC, the dominant drivers of change across Australian agriculture are climate, soil properties, and crop productivity. This does not imply that management is unimportant; rather, its effects may be more relevant at regional or local scales where site-specific conditions allow for greater impact. For carbon markets and climate policy, these results emphasise the need for regionally-calibrated baselines and mitigation expectations that reflect local climate, and yield potential.

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Keywords: *Soil organic carbon, modelling inputs, sustainable agriculture, stock change drivers*

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