Final report

Measuring Soil Carbon in Grazing Systems

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Abstract

Soil carbon sequestration in grazing lands offers potential for achieving MLA's goal of carbon neutrality by 2030. Two major constraints for demonstrating this potential are uncertainty around the best management options and the high cost of validating incremental stock changes in highly variable landscapes. This study tested eddy covariance "flux" towers, capable of monitoring highly sensitive changes in carbon sequestration and emissions at a landscape scale in two paddocks near Goondiwindi, southern Queensland. Results showed a significant increase in soil carbon at both sites using the towers, though only one site using intensive soil coring. The initial rainfall response at the end of the 2019 drought demonstrated the great potential for flux towers to help understand changes in soil carbon and provide accurate estimates of changes in the carbon and water cycles that traditional soil sampling could not pick up. While the relatively high upfront costs of flux towers limit their wide-spread deployment for direct measurement of every farm, increased mobility of equipment and combining with process models for upscaling across bioregions will greatly extend their applicability. **Annualised, a regionally calibrated model validated with flux tower data could represent as little as $3-$5 per hectare per year.**

1. Executive summary

Background

Increasing soil organic carbon (SOC) through improved grazing management practices is tightly linked to increasing soil health, drought resilience and the sustainability and profitability of Australia's pastoral industry. Recent policy changes by the Australian Government have resulted in fast-tracking innovative soil management practices in grazing systems as a priority for reducing the nation's greenhouse gas emissions. By storing carbon in soils, graziers can gain soil carbon credits, providing an additional income stream, ensuring continued access to current and emerging high-value low-carbon market opportunities, and aligning themselves with the Australian Red Meat Industries' carbon-neutral initiative (CN30). This research will examine the use of eddy covariance flux towers to measure the impact of time-controlled grazing on soil health, soil carbon, and water use efficiency. The project outputs provide a foundation for further work under projects P.PSH.2104 and P.PSH.2126. By significantly reducing the costs of soil carbon measurement (currently around $20-$30 ha) and increasing the certainty in the rate of C sequestration in Australian grazing systems, producers will gain greater clarity on the financial upside of carbon farming.

Objectives

- Confirm changes in SOC in response to grazing management at scale from two flux towers in Goondiwindi.
- Determine how this information can be used in the development of predictive models for pasture productivity and soil carbon change in response to climate and soil type.
- Develop a cost-effective and scalable solution to measure SOC and enable producers to better manage soils and generate soil carbon credits.

Preliminary outcomes to the objectives have been achieved but methods require further refinement under projects P.PSH.2104 and P.PSH.2126, which are still ongoing.

Methodology

Two eddy covariance towers were installed at a site in Goondiwindi to determine the impact of time-controlled grazing on SOC stocks. Over 2.5 years, data on Net Ecosystem Exchange of Carbon were measured, alongside measurements of above and below-ground biomass (pre and post-grazing) and tree carbon. This data will be used to inform predictive models for pasture productivity and soil carbon change in response to management.

Results/key findings

Eddy covariance flux towers can generate robust and defensible annualised estimates of ecosystem C exchange over large spatially averaged areas (up to 50 ha) suitable for a C accounting environment. More work needs to be done in projects P.PSH.2104 and P.PSH.2126 to account for C in different pools to determine the annualised C account from NEE. Above-ground biomass, below-ground roots and tree carbon must all be subtracted from NEE to determine soil carbon stocks.

Benefits to industry

This project provides the foundation to develop a cost-effective and scalable solution to measure SOC to inform producer decision-making and generate an income stream through carbon farming.

Future research and recommendations

The findings from this project will be used to inform work in projects P.PSH.2104 and P.PSH.2126.

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2. Background

Increasing soil organic carbon (SOC) through improved grazing management practices is tightly linked to increasing soil health, drought resilience and the sustainability and profitability of Australia's pastoral industry. Recent policy changes by the Australian Government have resulted in the fast-tracking of innovative soil management practices in grazing systems as a priority for reducing the nation's greenhouse gas emissions. By storing carbon in soils, graziers can gain soil carbon credits, which can provide an additional income stream as well as aligning themselves with the Australian Red Meat Industry's carbon-neutral initiative (CN30).

Research into the use of adaptive or time-controlled cell grazing as a valid management practice is being investigated by QUT on behalf of MLA using carbon dioxide (CO_2) measurement techniques (CO_2 flux towers) at two sites in the Goondiwindi region. Flux towers provide a non-destructive means of measuring the exchange of CO_2 and water between soil, plants and the atmosphere over relatively large areas (20-100 ha). The inherent spatial variability in plant production and soil properties across a landscape makes it extremely difficult to collect meaningful quantitative data on the impact of management practices on plant (and ultimately animal) productivity and the underlying SOC and water dynamics.

Because this research is currently limited to a specific climatic region and soil type (grey clay), maximum benefit to the livestock industry and its investors can only be achieved by additional research north into the tropics and on multiple soil types (black clays) to cover the wide diversity in soil/climate environments. By increasing the number of research sites from two to six, including additional CO_2 flux towers, the research will provide the required diversity in data to accurately inform graziers across Australia of the potential for carbon storage in their soils.

The original two CO_2 flux towers funded by the project have operated at Goondiwindi since December 2019. This report includes the data from these towers from December 2019 to May 2022 and accompanying biomass and soil carbon sampling data. This data has provided the foundation for future work in P.PSH.2104 and P.PSH.2126. Our high-resolution data sets will cut through some of the confusion in the soil carbon space and provide greater clarity to producers on the potential financial gain from soil carbon farming.

Flux tower at Goondiwindi, source David Rowlings

3. Objectives

- Confirm changes in SOC in response to grazing management at scale from two flux towers in Goondiwindi.
- Determine how this information can be used in the development of predictive models for pasture productivity and soil carbon change in response to climate and soil type.
- Develop a cost-effective and scalable solution to the measurement of SOC to enable producers to manage soils better and generate soil carbon credits.

The project has been successful in meeting the objectives. We have data sets from 2019-2022 on net ecosystem exchange (NEE), evapotranspiration and water use efficiency, biomass, and soil carbon data. This data will be used as a foundation to extend the research to other climatic zones and soil types in projects P.PSH.2104 and P.PSH.2126. This data will 'supercharge' predictive models for pasture productivity and soil carbon change in response to climate, soil type and management. The ultimate soil carbon measurement product (to be delivered in project P.PSH.2126) will result in a cost-effective and scalable solution to the measurement of SOC.

4. Methodology

4.1 Eddy covariance flux tower data

The two flux towers that form part of this foundational project are located on two paddocks managed by the same owner under a time-controlled grazing (TCG) systems near Goondiwindi (FT1 and FT2 – Figure 1). Flux towers are located on open fields located within the 'wagon wheel' paddock design, with fence lines radiating from a central watering point (Figure 2). Site histories differ slightly, with Paddock 1 (referred to as Flux 1 for the tower data) being under TCG since 2012 and Paddock 2 (Flux 2) under since 2017. An exclusion fence was installed around Paddock 2 in 2018 to reduce the heavy total grazing pressure from kangaroos.

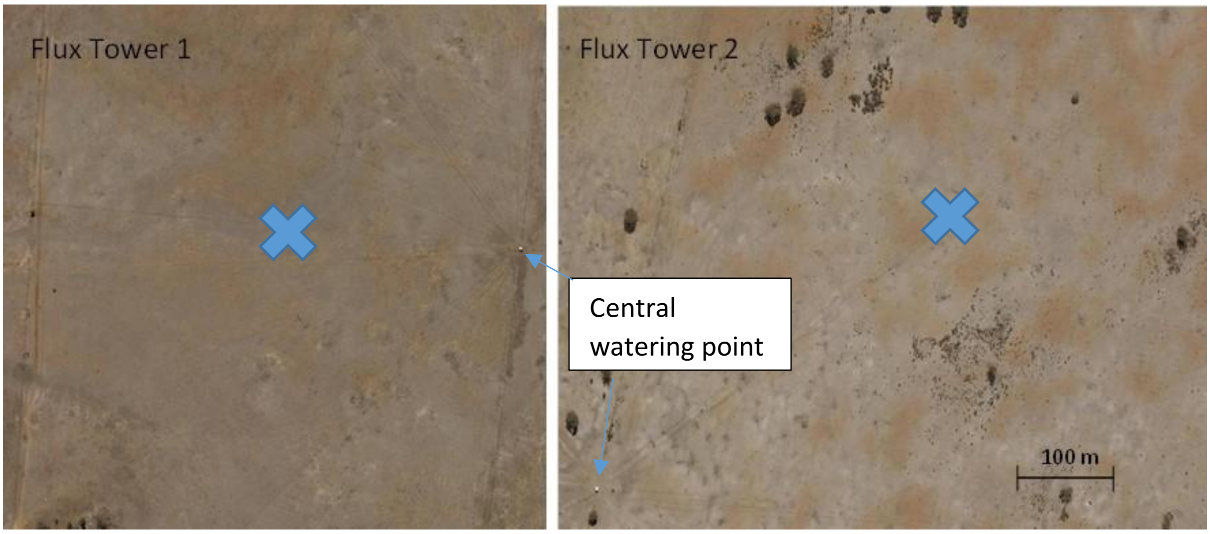
Figure 1: Location of the flux towers (Flux 1 and Flux 2) in southern Queensland (image courtesy of Google Earth)

Table 1 - Site condition summary for study sites A and B in Goondiwindi Region, Queensland.

Study Site	Flux 1	Flux 2
Dominant species*	40% - *Dichanthium sericeum* L. (Queensland bluegrass) *25% - Panicum coloratum L.* (Bambatsi Panic) 25% - *Urochloa mosambicensis* (Hack.) Dandy. (Sabi grass) 10% - Other	
Soil Classification (ASC) (Isbell, 1996)	Brown Dermosol, Grey Vertosol	
Soil Classification (USDA)	Alfisol,Vertisol	
Bulk Density (g cm^{-3})^	1.44	1.39
Texture Class^	Clay	Clay
Sand:Silt:Clay (%)^	31:24:45	39:16:45
CEC (cmol kg^{-1})^	37.6	34.2
Soil pH^	8.2	8.6
C:N Soil^	12:1	10:1

*Dominant species generalised from species-level observations available for 76 above-ground biomass samples. ^ Soil parameter calculated as the mean of the two dominant soil types at each study site from measurements in the 0-30cm layer.

Figure 2: Position of flux towers marked by blue (+). Grazing "cells" can be seen radiating from a central watering point. Differences in soil type (red earths and grey clays) across the measurement area are evident (image courtesy of Queensland Globe).



Measurements of CO_2 gas flux in and out of an ecosystem are commonly undertaken using the eddy covariance technique. The method relies on the direct and rapid measurement of actual CO_2 transport by a 3-dimensional wind in real-time in the field.

The original two CO_2 flux towers funded by the project have operated at Goondiwindi since December 2019. These sites are also the location of soil C sampling for Government registered C offset projects by a commercial soil carbon project developer. These sites differ in clay content, influencing water movement and biomass production, making soil C accounting for traditional soil sampling methods highly complex and expensive.

The original two sites at Goondiwindi are approximately 7 km apart, with particular care in selecting a similar distribution of soils at both sites. Both sites are managed under adaptive/time-controlled grazing, with Flux site 1 converted in 2012 and Flux 2 in 2017 (Figure 4).

Data collection has continued from the Goondiwindi site for the 2021-22 period. Along with flux tower inputs (Net Ecosystem Exchange (NEE) – CO_2, evapotranspiration, phenocams), extensive spatial sampling of soil moisture, biomass productivity and diversity of pasture species has been collected quarterly across the two sites. For comparison with standard soil sampling, a second round of spatial soil analysis was conducted in January 2022 at the same spatial coordinates as the initial sampling (December 2020). Vegetation was collected across the sites along two perpendicular north/south – east/west transects with pasture composition and dry matter biomass yield collected at 10 m intervals.

4.2 Ecosystem Carbon Balance

To enable a comparison between a soil coring inventory method and the eddy covariance flux towers, we need to account for all the carbon flows from the different paddocks. This approach, called the Net Ecosystem Carbon Balance (Figure 3), ensures carbon stored in the biomass (NPP – Net Primary Productivity) and removed via grazing is accounted for, and any remaining carbon can be attributed to below-ground. Root NPP (BNPP) and <2mm plant material is measured via the soil sampling process and subtracted from the soil organic carbon pool. Animal respiration and carbon removal in livestock (R_{animal}) was calculated using stocking rate records provided by the farmer.

Figure 3. Equations to calculate Net Ecosystem Carbon Balance using eddy covariance.

$$\mathrm{NEP} = \mathrm{NPP} - (R_{microbe} + R_{animal})$$

Subtract grazer respiration from NEP

$$\mathrm{NEP} - R_{animal} = \mathrm{NPP} - R_{microbe}$$

Partitioning NPP into above and below-ground components.

$$\mathrm{NEP} - R_{animal} = (\mathrm{ANPP} + \mathrm{BNPP}) - R_{microbe}$$

Separation of below-ground fluxes from the rest of the ecosystem

$$\mathrm{NEP} - R_{animal} - \mathrm{ANPP} = \mathrm{BNPP} - R_{microbe}$$

Component	Measurement technique
NEP	• EC, LI-7500DS/Gill WMP/SmartFlux3 • New software suite based on PyFluxPro • Uncertainty Hollinger & Richardson only.
R_{animal}	• Digital grazing records, 19 days over 2.5 years • Exclude dates in EC processing when animals present.
ANPP	• Destructive quadrat sampling - Change in standing live C and detached pasture litter. Digital grazing records – Estimated removed live C by domesticated grazers that we did not capture.
BNPP + $R_{microbe}$	• Soil coring – change in both >2mm and <2mm fractions. • Equivalent soil mass corrections for changes in soil mass at depth

Figure 4. Aerial image of Flux two showing the tower and pasture biomass cuts (top) and during the grazing event on 24 April 2020 with 450 LSU for 24 hours (middle and bottom). The high heterogeneity of the landscape is evident both in soil type and biomass production.

4.3 Soil sampling

A hydraulic-push soil rig was used to collect deep (100 cm) soil samples for baseline analysis of soil carbon for comparison with long-term flux measurements as well as associated soil properties. Twenty-three soil profile cores per site were collected from random locations across the 15 ha tower footprints in 2019, and resampled from the same locations four times over the 2.5 year study. Cores were collected using a 50 mm hydraulic push core to as deep as possible, with the majority collected to at least 1 m and one-third to 1.6 m depth. Maximum rooting depth and abundance and colour were recorded, as well as total weight for bulk-density, though this was of limited success to dry conditions at sampling. Soils were bagged into 10, 20, 30, 50, 70, 100, 130 and 160 cm depth increments and kept cool and transported back to QUT for analysis. A total of 265 individual samples were analysed from the 46 soil cores.

Soil were dried at 60 °C, sieved to 2 mm and ground prior to analysis. All samples were analysed for total carbon and nitrogen (TC and TC %) by dry combustion on a LECO CNS analyser. All soils were visually tested for inorganic carbon using the HCl effervescence test, and samples, where a reaction was observed (40% of samples), were treated with 2M H_2SO_4 prior to re-analysis on the LECO for total organic C (TOC). Carbon stocks were calculated by adjusting for bulk density and summing down the profile.

Major cations were analysed on eight profiles per site (2 per soil type) by aqua regia digestion for analysis on an ICPOES, and concentrations, base saturation and CEC calculated. Inorganic N (ammonium and nitrate), pH and EC were also analysed on this subset samples, as was soil texture.

4.4 Biomass estimation

Accurate estimates of biomass production and removal via grazing are essential for closing the C balance and were measured using several different approaches over the study. Biomass was initially harvested from ten, 25 m^2 quadrants, along with cover estimates and species composition (Figure 5). Biomass was cut using a lawn mower to a residual height of 5 cm. Fresh weights were recorded for both the whole plot and a representative subsample which was subsequently dried at 60 °C at the QUT laboratory. Harvests were conducted at maximum biomass in mid-March, and pre and post-grazing events on the 24 April and 26 May 2019 for Flux 2 and 1, respectively. Cuts were also calibrated against phenocam and photo standards.

Figure 5: Pasture biomass harvests at Goondiwindi in March (left) and pre-grazing in May 2020 (Flux 2) left. Photo David Rowlings

Biomass cuts were also taken on a grid basis as part of a botanal survey conducted in May 2021 and 2022. A minimum of 50 0.5x0.5m cuts were collected along with species composition and yield estimate for a 10 m radius of the cut. Samples were geolocated with a high-precision GPS and analysed for biomass, carbon and nitrogen content and lignin for later comparison with satellite data.

4.5 Biogeochemical process modelling

The globally proven DayCent model has been utilised for initial simulations of NEE and translation to soil C change in response to management. DayCent is the underpinning model for the United States official greenhouse gas inventory in agriculture and carbon markets. QUT is working closely with the Colorado State University developers of DayCent. The FullCAM model is also being tested. Results are still preliminary and not presented in this report.

4.6 Selection of additional flux tower sites

As part of the variation to the existing agreement with contributions from McDonald's Australia, two additional paired sites (2 pairs of control – conventional grazing, and TCG) were required. The similarity between sites is not as critical for flux towers as for paired soil sampling, as the towers measure carbon flows and are less influenced by the long-term site history. Therefore, Site selection criteria focus on reducing variability in the eddy covariance (flux) method, with flat, evenly grassed/treed sites preferred.

4.7 Industry engagement

This project has had a major impact on how the industry accounts for carbon as well as getting near real-time feedback on pasture improvement and management strategies. Through the demonstration of the towers in the project, a new project was developed, funded via McDonalds, TUROSI and Rabobank through MLA's Carbon Storage Pathways (CSP) program, and has led to the deployment of the additional four towers.

The preliminary results presented at the CRC-P project summary in Townsville, August 2020, also prompted Agrimix to invest in an additional nine towers which have since been deployed as part of the CSP Measure Model Validate project led by Agrimix. In total there are now 17 towers across Queensland collecting critical information on pasture improvement productivity, water-use and carbon sequestration. Other companies which have engaged with the technology include Packhorse (a new MDC project including 3-5 towers is currently being developed), NAPCo, Paraway, Queensland Trust for Nature, the Office of the Cabinet for the Japanese Government, as well as the dairy (Dairy Australia) and grains industry (GRDC for mixed farms). Through the Agrimix partnership, a Measure Model Verify method is expected to be developed in the next 2-3 years which will greatly increase the accessibility of carbon projects to farmers in lower rainfall zones and assist in decision-making around pasture improvement and management.

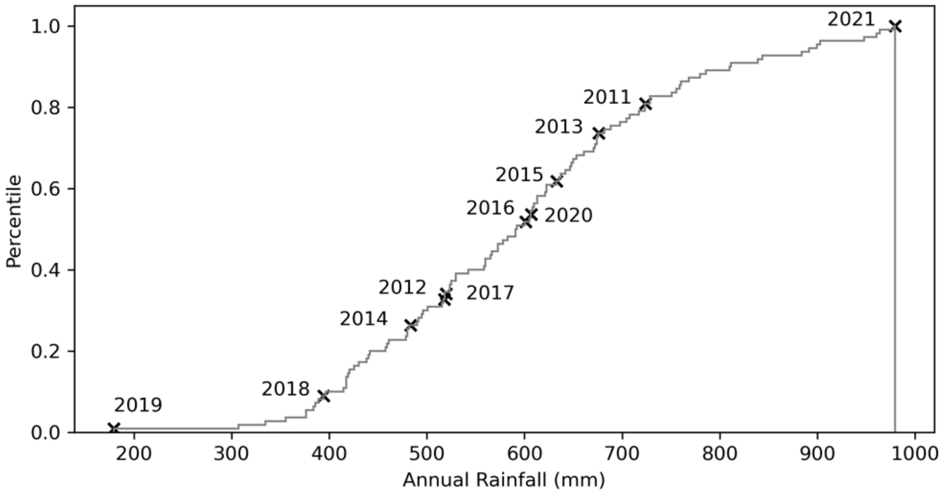
5. Results

5.1 Climatic conditions during the study

The preceding years (2017-2019) to the study were characterised by severe drought (Figure 6), culminating in the driest on record for the region (Bureau of Meteorology, 2021). Following the study commencement, these conditions were broken by summer rainfall beginning in January 2020 and continuing into the highest annual falls since station records began (1910) in 2021. Above-average precipitation continued into the first half of 2022.

Soil water was highest in autumn and winter of 2021 when unseasonally high precipitation persisted. Aside from this anomalous period, we see typical climate dynamics for the region for the balance of the study period – large rainfall associated with thunderstorms during the summer growing season and dry, cool off-seasons.

Figure 6 - Cumulative probability distribution for annual rainfall (1910-2021) for study sites in Goondiwindi Region, Queensland. Measurements were retrieved from a nearby national bureau station. Years (2011 to 2021) annotated.



5.2 Flux tower data

Cumulative 80% footprints for the study period were ~3 ha per site, and followed the prevailing streamlines of the site we estimated from our pre-deployment study. The trial tower sensors were positioned at the lower end (3.6 m) of their potential height to ensure areas of trees and regrowth were excluded from the analysis. The 20m x 20m exclusion cage at site A was not captured by the 80% footprint estimation. Figure 7 shows a diagram of the study sites showing the 80% footprint of flux tower (centred) in relation to soil and pasture (transect) sampling sites, sampled at repeat intervals. All biomass and soil samples were collected from within the flux tower footprint.

Figure 7: Schematic diagram of Flux 1 and Flux 2 sites showing; 80% footprint of flux tower (centred) soil and pasture (transect) sampling sites, sampled at repeat intervals. Centroid of 20m x 20m pasture exclusion cage additionally shown. Displayed with a projected coordinate system centred [0,0] around flux tower. Image underlay showing areas of regrowth: Sentinel 2 (© European Space Agency – ESA) (Acquistion Date: 28th June 2022)

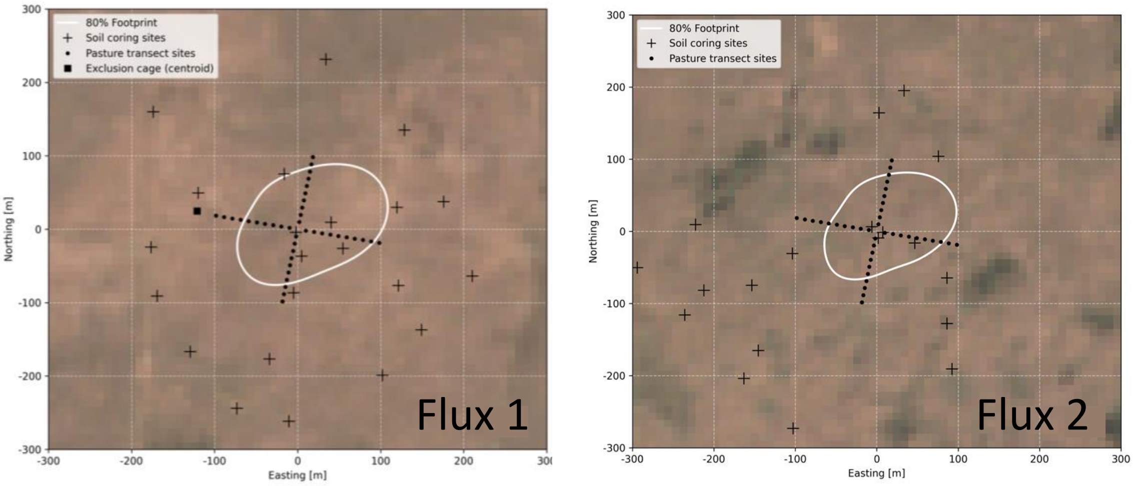


Figure 8. Daily rainfall and Net Ecosystem Exchange from Flux towers 1 and 2 December 2019 – April 2022

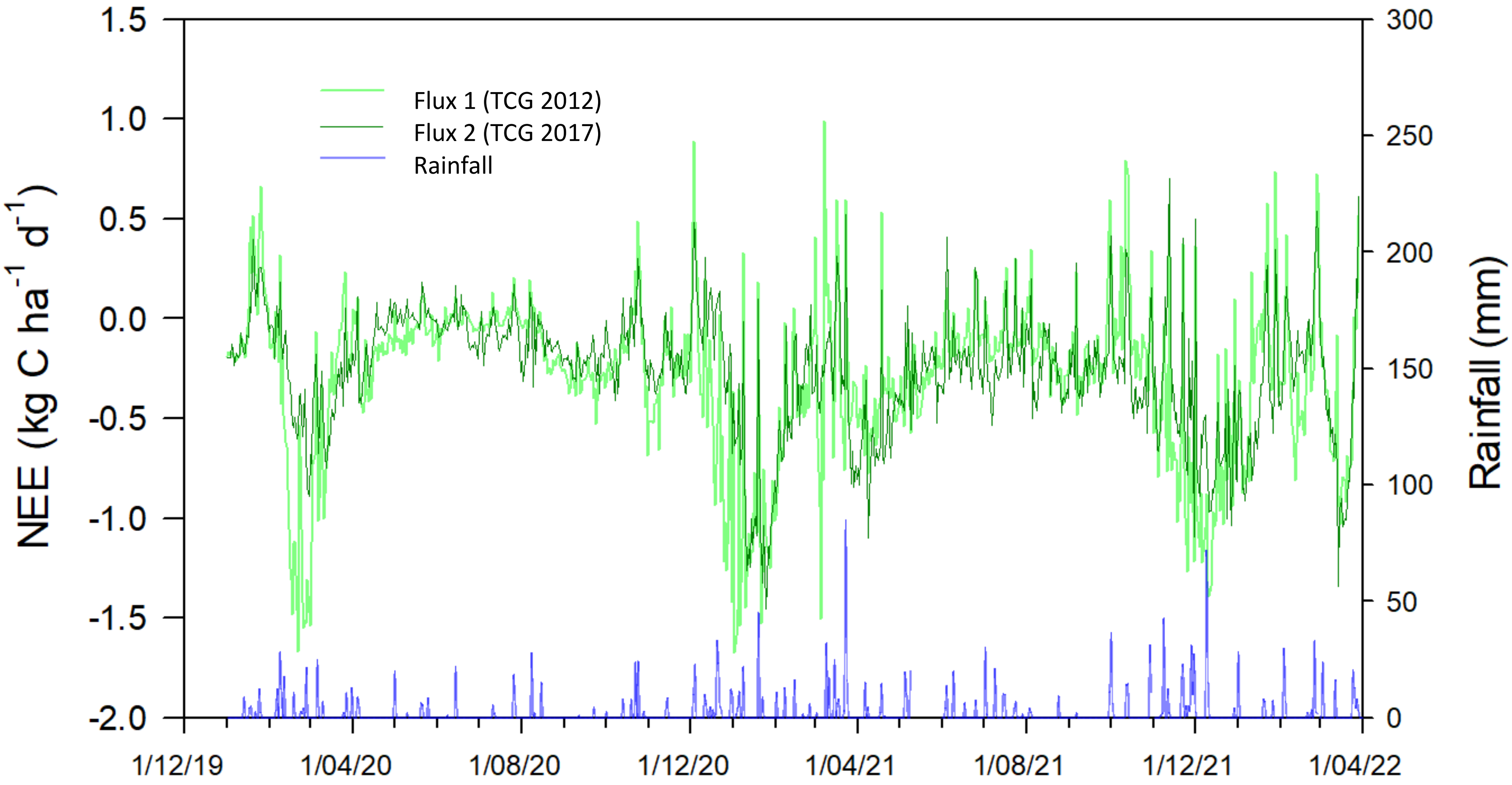
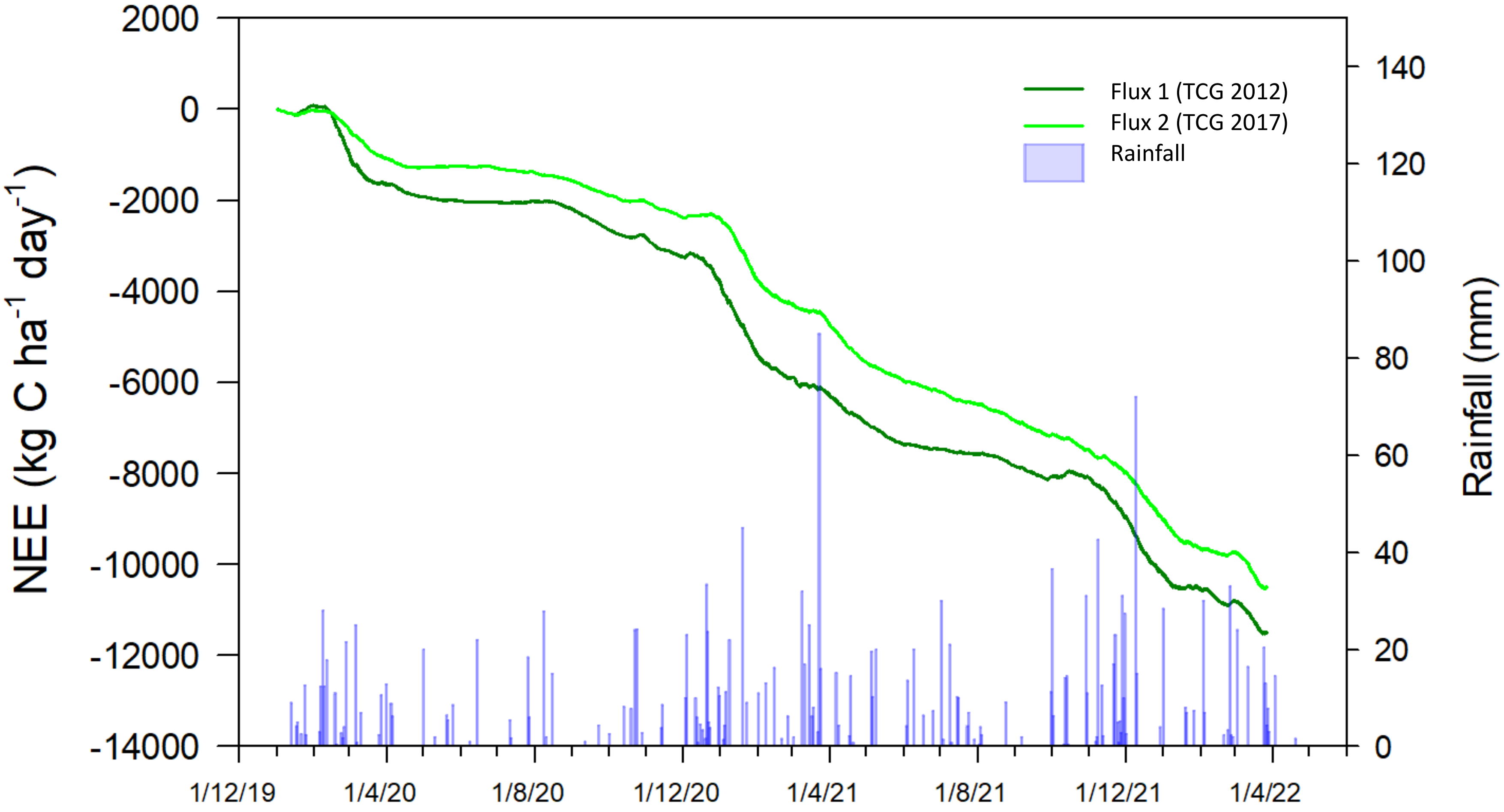


Figure 9: Cumulative C uptake (biomass and soil) from Flux towers 1 and 2 December 2019 to April 2022



Following the first rainfall in mid-January 2020 (Figure 8), daily Net Ecosystem Exchange (NEE = net carbon sequestration or emission) showed the soil was initially a short-term net source of carbon (Figure 9) as an increase in microbial activity promoted decomposition of pasture residues and soil carbon (emitting CO_2) faster than the plants could recover and begin photosynthesis (sequester CO_2). A net total of 230 kg C ha^{-1} was lost during this two-week period before the paddock became a net sink, corresponding roughly to the emergence of the blue grass seedings seen in Figure 10. Similar spikes in decomposition and CO_2 emissions were observed after other rain events, particularly later in the season as microbes responded faster than the pasture. Maximum growth rates of 150 kg C day^{-1} were obtained following good summer rainfall in 2021-22, with carbon drawdown continuing year-round following good winter and spring rain. Over the 2.5 years of the study total NEE, or carbon drawdown was >11.4 t/C/ha for Flux tower 1 and >10.4 t/C/ha^{-1} for Flux tower 2. Of this ~3-5 t C ha^{-1} was standing pasture biomass, ~1-4 t C ha^{-1} associated with below ground (roots) carbon change and 171-225 kg C removed in the animals.

5.3 Above ground biomass

The above-ground biomass showed significant temporal variation, particularly as measurements started during an extremely dry period (2019) (Figure 10), where in some quadrats, there was no biomass to sample, to 2022 where the region had experienced wetter than usual conditions (Figure 11). Changes in above-ground biomass (measured by pasture cuts) over the experimental periods are shown in Figure 12 and biomass removed through grazing can be seen in Figure 13.

Manual biomass cuts were compared against proximal estimates of animal consumption. Recorded large-stock units (LSU) data from the land manager was converted to daily fee in-take for maintenance and estimated daily growth rate and was assessed against measured events using biomass cuts over two time intervals. Predicted growth was within the 95% confidence interval on both occasions, with a predicted pasture removal of 521 kg DM ha^{-1} vs 481 measured kg DM ha^{-1}, and 248 kg DM ha^{-1} vs 267 kg DM ha^{-1} measured, respectively. These estimates fit the spatial error associated with paddock scale pasture variability.

Figure 10: Phenocam images of pasture cover at Flux 2 at the start of the experimental period (December 2019)

Figure 11: Biomass sampling at the beginning (December 2019) and end of the experimental period (April 2022). Photo David Rowlings.

Figure 12 Above ground biomass for flux tower 1 and 2 in experimental period December 2019 to April 2022

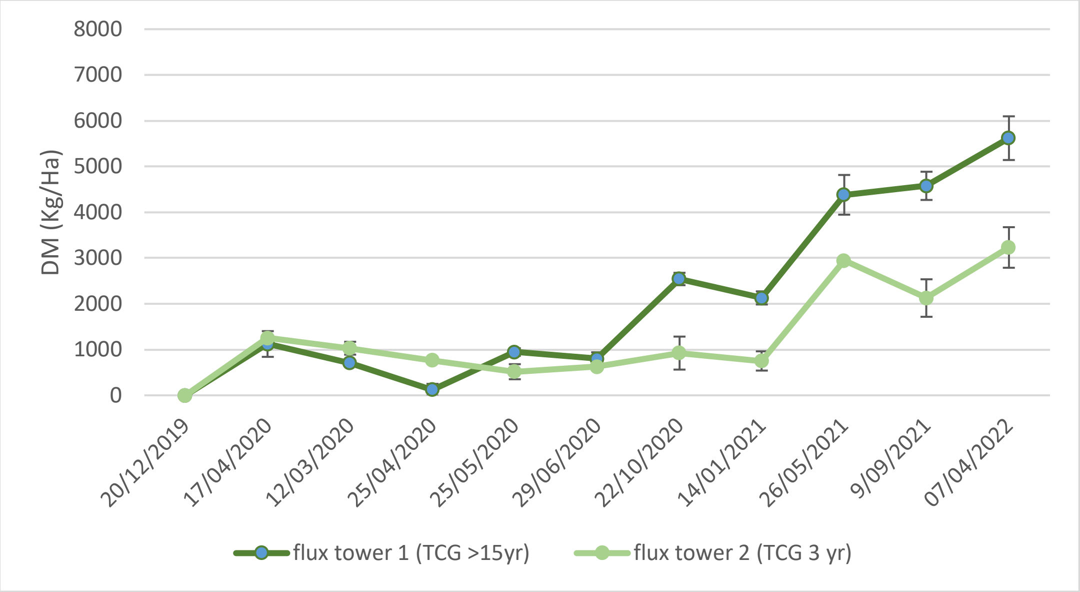
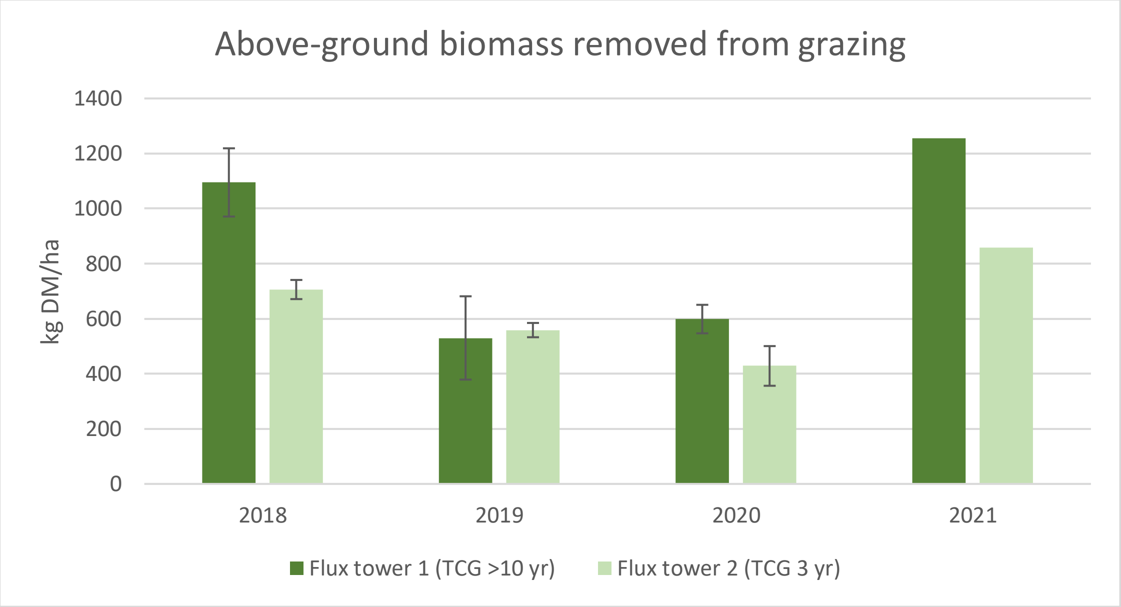


Figure 13: Biomass removal from grazing over the experimental period December 2019 to April 2022



5.4 Soil carbon data

Pasture growth following the break of the drought in early 2020 responded to record rainfall across the 2021-22 season and, combined with lower-than-average stocking rates, led to high amounts of standing biomass. Pasture response was substantially greater at Flux 1, which soil coring demonstrating a significant ($P>0.001$) increase in carbon by 2.2 t C per ha per year (Figure 14, Table 2). This corresponded to an average increase in TOC of 0.15% to 1m, and 11.3 t CO_2 ha^{-1} $year^{-1}$. This is likely higher than the long-term potential sequestration as the extremely high pasture biomass at the time of final sampling would have been comprised of a large component of labile carbon (which is readily lost from the soil system).

This relatively large average change in soil carbon over 2.5 years should be viewed cautiously, as the final soil sampling at 2.5 years has potentially skewed the regression analysis. The trend in soil carbon over the first 2 years are more consistent with biomass measurements taken on the field and the carbon uptake values measured at the flux tower. Badgery et al. (2020) found large temporary changes in soil carbon in similar grazing systems that have subsequently decreased. It is recommended that further soil sampling be undertaken at the 3-year point to have full confidence in the trend observed.

Soil cores taken from Flux 2 showed no significant increase in carbon to 100 cm, with average SOC levels actually decreasing over the monitoring period at depth (Figure 15, Table 2).

Both sites lost carbon during the first sampling period (December 2019 to January 2021), though substantially more was lost from Paddock 2 at depth (-2 t C ha^{-1}). The majority of the gains in carbon measured from Paddock 1 was sequestered between the 2nd and 4th sampling events.

Figure 14. Change in soil carbon over the 2.5 year study according to the soil sampling at Flux 1 site. Data is displayed for the 0-30 cm and 0-100 cm soil depth.

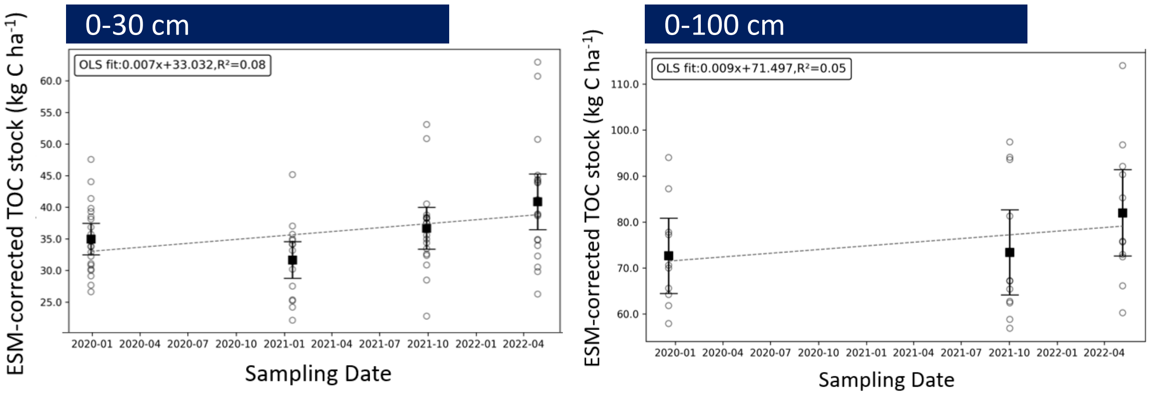


Figure 15. Change in soil carbon over the 2.5 year study according to the soil sampling at Flux 2 site. Data is displayed for the 0-30 cm and 0-100 cm soil depth.

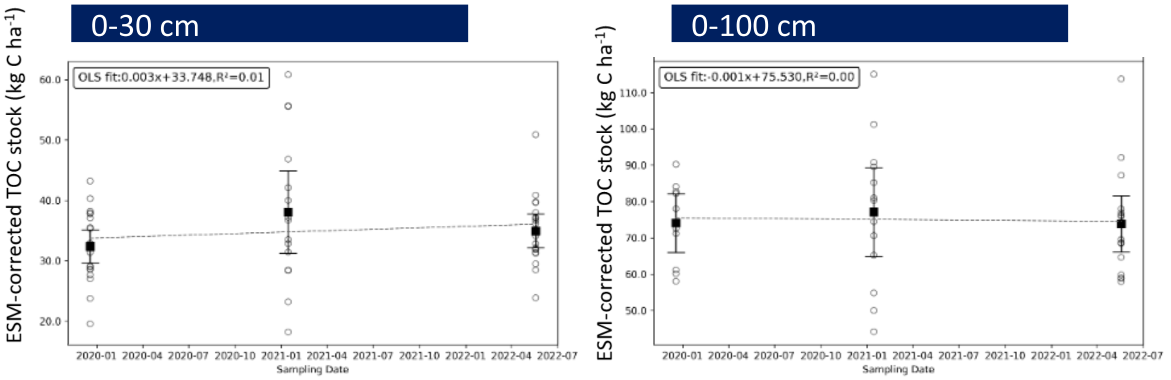


Table 2. Summary of soil carbon sequestration over the 2.5 years of the study

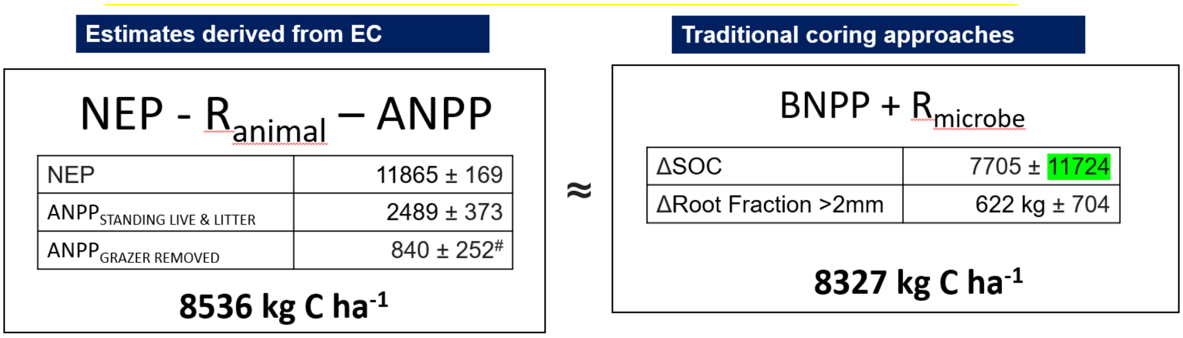
Paddock	Soil depth	Baseline carbon (t/C/ha)	Total carbon change (t/C/ha)	Total CO_2e seq (t/C/ha)	Annual carbon seq (t/C/ha)	Annual CO_2e seq (t/C/ha/yr)
1	0-30 cm	33.0	5.5	20.2	2.2	8.1***
	0-100 cm	71.5	7.7	28.3	3.1	11.3***
2	0-30 cm	33.8	2.7	9.1	1.1	4.0
	0-100 cm	75.5	-1.4	-5.1	-0.6	-2.1

*** significant at P=0.001

5.5 Comparison between soil carbon estimates using inventory vs NECB eddy approach

The NECB and soil inventory approaches matched well with considerably less uncertainty. At flux 1, the two approaches were within 200 kg C ha^{-1}, with the NECB approach showing considerably lower uncertainty (0.2 vs 11.7 t C ha^{-1}). By using the NECB approach, we could also provide additional evidence to increase our understanding of soil carbon dynamics in pastoral systems. For instance, the high sequestration rates measured at this site suggested a below-ground allocation of carbon 2.5 times higher than above-ground, far greater than the widely assumed 40%. These findings, within the context of the extreme climatic variation experienced in the study, demonstrate how limited our understanding of pasture, carbon and climate dynamics are in Australian grasslands.

Figure 16. Comparison of the Net Ecosystem Carbon Budget approach and traditional soil c inventory using soil sampling.



Estimates derived from EC

$NEP - R_{animal} - ANPP$

NEP	11865 ± 169
$ANPP_{STANDING\ LIVE\ \&\ LITTER}$	2489 ± 373
$ANPP_{GRAZER\ REMOVED}$	840 ± 252$^{\#}$

8536 kg C ha^{-1}

≈

Traditional coring approaches

$BNPP + R_{microbe}$

ΔSOC	7705 ± 11724
ΔRoot Fraction >2mm	622 kg ± 704

8327 kg C ha^{-1}

5.6 Pasture management implications from flux tower data

The 2019 drought resulted in no pasture growth and minimal surface cover until the first significant rainfall in mid-January 2020. Between 230 mm and 270 mm fell across the sites until the end of May 2020, providing good pasture growth conditions. The extreme conditions at the start did, however, provide a unique opportunity in pasture systems for initial zero conditions to be determined, not only for CO_2 sequestration, but also pasture growth. Phenocam images from Flux 2 demonstrated the difference between live (barely) tussocks *versus* the regrowth of Qld Blue Grass from seed (Figure 17). The tussock was able to respond substantially faster to the rainfall, reaching flowering before the blue grass had established full ground cover (11th Feb). Over the same period 60 mm of evapotranspiration was measured, equating to ~40% of rainfall being lost before any pasture production could occur. A full video of the pasture growth time-lapse is available here: https://www.youtube.com/watch?v=C-5bBPVJ-1k&feature=youtu.be (best viewed in HD).

This explains the large discrepancy in soil carbon estimations observed between the two sites, with the slow response of the pasture to rainfall at Flux 2 contributing to the carbon loss observed during this period. During drought, substantial amounts of roots and soil microbes senesce and die due to desiccation. However, this highly labile pool of carbon and nitrogen is not actually lost from the soil until soil moisture again allows for a burst of decomposer activity. The carbon balance at this time is highly dependent on the balance between decomposition C losses and new plant inputs, with the slower pasture response in putting in less C compared to Paddock 1 and resulting in a net loss of C.

The high flush of labile N and lack of new C inputs during this period may also have forced the microbes to utilise existing C to meet their energy requirements, leading to the mining of soil C (also known as negative priming). This may have been exacerbated at depth due to the extended period of time before new deep roots were established, explaining the disproportionate loss of C from this layer.

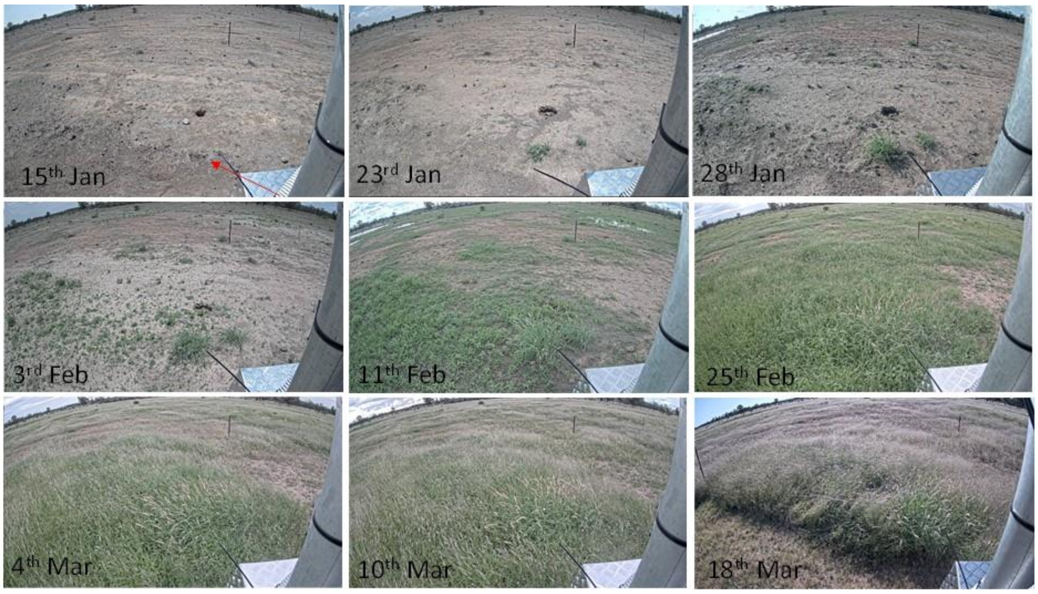
Some large uncertainties still exist for the implementation of towers for accurate soil C budgets. The change in below-ground biomass (roots) is extremely difficult to measure and can have a large impact if not properly accounted for. In this study, this uncertainty was exacerbated by the commencement of monitoring in December after a record drought when there was no biomass and the ceasing of measurement in May after two record years when biomass was at the absolute maximum. Longer measurement periods and commencing in more typical conditions allow for these uncertainties to be largely reduced, though more work is required to quantify below-ground carbon inputs.

Further analysis is required to understand the difference in carbon sequestration estimation between the soil sampling and the flux tower. At Flux 2, soil sampling showed no net C change, whereas the towers showed a small gain of up to 2.4 t C ha^{-1} year. At Flux 2, this can largely be attributed to woody thickening across the site (see Figure 3) which grew rapidly with the good seasonal conditions. At Flux 2, the sequestration from the tower was ~one-third of that from soil sampling and be potentially attributed to:

1. Spatial errors in above and below-ground biomass estimation.
2. Uncertainties in animal carbon consumption and in capturing animal respiration with the towers.
3. Spatial discrepancies between soil sampling locations and flux tower footprint.
    a. A number of initial soil sampling locations couldn't be accessed in subsequent samplings due to wet conditions (bottom of the melon holes). These areas could have been losing carbon but picked up by the flux tower.
    b. 23 samples may not have adequately captured the highly heterogeneous soil conditions at the site.

To overcome these issues in the future, two additional towers have been placed in fields converted from cropping where starting conditions are expected to be more homogenous.

Figure 17. Phenocam time-lapse images of pasture response to rain from Flux Tower 2 at Goondiwindi. 19 mm of rain fell on the 16th January, with an additional 210 mm falling over the remainder of the displayed period. Red arrow highlights the surviving Buffel tussock.



5.7 Additional sites

Table 3. All additional sites have been confirmed and flux towers have been installed at all sites. Data collection and processing has commenced and will be reported under P.PSH.2104.

Site	Grazing system	Soil type	History
Rolleston	Rotational buffel grass	Brigalow/clay	
Rolleston	TCG with trees	Brigalow/clay	TCG for 20+ years
Baralaba	TCG	Alluvial clay	TCG for 6 years
Billa Billa	Conventional	Grey vertosol	Conventional bambatsi/buffel >30 years
Canowindra	TCG	Vertosol	Rotational grazing
Meandarra	TCG	Brigalow/clay	Conventional grazing/ fodder cropping 30 + years. Converting to TCG 2022.

5.8 Cost analysis of the flux tower approach

The soil sampling methodology employed in this project was able to detect a significant change in soil C at one paddock but not in the other. The density of cores collected (~2 per hectare) exceeded that of any commercial project by a factor of 10 to 100. In addition, subsequent sampling events were based around the same points, reducing a lot of the random spatial variability and allowing more sensitive detection of change. This is not permitted under the current ERF guidelines and, together with a lower sample rate, it's unlikely soil C change would have been detected (over 2.5 years) under a commercial project without large discounts.

Arguably, far more samples are required in complex terrain/heterogeneous landscapes to gain a reliable estimate of the mean carbon stock, and 23 cores over 100 ha may be feasible. Even at this extremely high coring rate, the amount of soil collected is equivalent to a hole the size of a 50 cent coin in a field as large as the Melbourne Cricket Ground. Assuming analysis costs of $75 per sample plus an additional $100 per sample for collection, the total sampling costs using 23 cores over 100 ha exceed $80 ha^{-1}. Further spatial analysis of the dataset and bootstrapping (to generate theoretical soil sampling regimes) will allow a fairer comparison between approaches.

The large measurement footprint of the towers allows an integrated value over the highly heterogeneous sampling area, with 80% of the flux estimation being measured over an area 3 hectares, with potential to increase further according to the size of the paddock. The tower height determines the size of the flux tower footprint. In this study, we wanted to limit the footprint within two grazing cells, but the tower height could potentially be increased 50-100% to integrate a much larger area. The higher sensitivity of the towers to detect changes compared to the coarseness of traditional soil C analyses also negates the high upfront costs of the tower, while the process level understanding of the drivers of soil C change and high-resolution data allow us to 'supercharge' plant-soil process models to upscale measurements across landscapes.

The application of the Eddy covariance technique for measuring soil carbon is rapidly evolving, but it still presents a high technical barrier for non-experts, particularly in data analysis and interpretation. Upfront capital costs are relatively high ($100,000 AUD) with a well-maintained system having a lifetime of 10 years. Maintenance and data analysis costs per annum are estimated at $10,000 per tower. If we assume one flux tower per 5,000 hectares, this equates to a sampling cost of around $4 per hectare per year over 10 years.

6. Conclusion

6.1 Key findings

A well-maintained system with good data processing procedures, under ideal site characteristics with care taken to demonstrate good surface energy budget closure, would generate robust and defensible annualised estimates of ecosystem C exchange over large spatially-averaged (up to 50 ha) suitable for a C accounting environment. It is important to note that the concept is not to have a flux tower at each site measuring soil carbon; rather, the flux tower data will be used to 'supercharge' soil carbon models and used in a strategic network to validate model outputs. It is anticipated that larger landowners (5000 hectares +) would have a flux tower on their property, while smaller landholders would rely on a regional network of flux towers.

We propose the following as the most reasonable and cost-effective application of eddy covariance theory in a C accounting environment in Australia; An industry, Government and producer-supported network of eddy covariance stations to collect data from (a) long-term (multi-decadal) regionally representative pastoral "reference stations", and (b) well-designed and well-executed short term factorial experiments on management change effects for modelling and extension. The identification of key measurement periods combined with additional inputs from remote sensing and modelling could potentially see flux towers becoming an essential tool in validating soil carbon sequestration methodologies and offsets.

These two datasets, alongside auditable producer-input management data and remote (or proximal) sensing data, could generate a modelling environment to generate robust and defensible estimates of C sequestration suitable for a crediting or whole-farm (GHG/LCA) audit scenario. Such estimates would need to be discounted to a conservative value as a trade-off to producers to recognise the increased uncertainty discounts associated with applying regional scale estimates to paddock scale. Producers would need to recognise that such discounting would be in lieu of needing to conduct onerous soil coring measurements.

The application of the eddy covariance technique to a modelling approach to soil C accounting could address the perceived shortcomings of the two currently approved soil C methodologies under the Emissions Reduction Fund (ERF) in Australia; (1) the overly conservative values constrained by a lack of adequate modelling data in (Estimating sequestration of carbon in soil using default values method (model-based soil carbon) – 2015). (2) The scale issues and risks of the introduction of unintentional or intentional systematic bias associated with repeat soil coring in (Carbon Credits (Carbon Farming Initiative—Estimation of Soil Organic Carbon Sequestration using Measurement and Models) Methodology Determination 2021).

6.2 Benefits to industry

- Higher resolution, real-time measurements of management practices on carbon stocks in their landscape.
- A system for measuring soil carbon that dramatically reduces sampling costs from around $20-30/ha to around $4 per hectare.
- High-resolution data sets to demonstrate to the whole of industry the impact of management on carbon and productivity.

7. Future research and recommendations

More research is required under projects P.PSH.2104 and P.PSH.2126 to generate longer-term data sets. This will overcome some of the difficulties in this project where we were accounting for carbon from drought conditions (2019) to above-average rainfall (2022). We have learnt lessons from this foundational project and realise the need for better data to account for carbon in different pools at the end of the measurement cycle. In particular, accounting for C in root biomass and C in tree re-growth. Furthermore, we must ensure that we are adequately capturing CO_2 respired from livestock and C exported in animal products.

8. References

Badgery, W.B., Mwendwa, J.M., Anwar, M.R., Simmons, A.T., Broadfoot, K.M., Rohan, M. and Singh, B.P., 2020. Unexpected increases in soil carbon eventually fell in low rainfall farming systems. *Journal of environmental management*, *261*, p.110192.