Carbon sequestration at Jigsaw farms

Report to Mark Wootton and Eve Kantor

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1 INTRODUCTION

This report provides estimates of the carbon stocks in planted trees at Jigsaw Farms in south-west Victoria. The family property of Mark Wootton and Eve Kantor is 15 kilometres north of Hamilton and has an area of 3147 ha. It integrates agroforestry, carbon, and indigenous plantings with high-productivity grazing on a large scale while adhering to environmental principles. The enterprises are a fine wool sheep flock, a prime lamb operation, an Angus/Poll Hereford breeding program, and an agroforestry operation consisting mainly of Spotted Gum (*Corymbia maculata*).[1]

The land type, climate and nature of the indigenous woody vegetation largely determine the potential for carbon sequestration through tree planting. Jigsaw Farms is located on two land systems – the Hensley Park property is on the Victorian Volcanic Plain while the Melville Forest property to the north west is on the Dundas Tablelands. Elevations range from about 220 to 280 m asl.[2] The geology at Hensley Park is Quaternary basalt from newer volcanic flows while at Melville Forest the geology is predominantly marine and non-marine sediments.[3] Soils are mainly grey sodosols[4], chromosols and vertosols at Hensley Park, and chromosols at Melville Forest.[5] Long-term (1984-2022) average rainfall at Hamilton Airport, approximately 6 km south of Hensley Park, is 615 mm per year.[6]

The property has large areas of remnant River Red Gum (*Eucalyptus camaldulensis*), mostly as paddock trees with some small patches of remnant forest. The main pre-1750 Ecological Vegetation Classes (EVCs) at Hensley Park were 'Plains Grassy Woodland' (EVC 55), an open eucalypt woodland of River Red Gum with a sparse understorey over a species-rich grassy and herbaceous ground layer (~ 40% of the property); 'Plains Grassland' (EVC 132_61), described as 'treeless vegetation mostly less than 1 m tall dominated by largely graminoid and herb life forms' (~ 40% of the property)[7]; and 'Creekline Grassy Woodland' (EVC 68), eucalypt-dominated woodland of River Red Gum to 15 m tall with occasional scattered shrub layer over a mostly grassy to herbaceous ground-layer (~ 20% of the property). At Melville Forest, the main EVC was Plains Grassy Woodland.[8]

When Jigsaw Farms was a larger holding of 4900 ha it was used as a case study in which the carbon balance of the agricultural enterprises was calculated (Doran-Browne et al. 2018). The study found that from 2000 to 2014 nearly half the greenhouse gas emissions produced by livestock (at an average stocking rate of 20–22 DSE per ha), fuel and energy were offset through carbon sequestration in trees and soil.

A similar study was undertaken by the University of Melbourne in 2022. This paper reports the estimates of carbon sequestration by planted trees undertaken as part of the study.

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[1] *https://www.jigsawfarms.com.au/who-we-are.*

[2] *https://maps2.biodiversity.vic.gov.au/Html5viewer/index.html?viewer=NatureKit.*

[3] Geological Survey of Victoria (1997), *Hamilton SJ 54-7, 1:250,000*; Geological Survey of Victoria (2003), *Dundas and part of Wannon, 1:50,000.*

[4] Soil pit site on Hamilton 1:100,000 map sheet, which is located on Hensley Park: *https://vro.agriculture.vic.gov.au/dpi/vro/glenregn.nsf/pages/glenelg_sm02.*

[5] *https://vro.agriculture.vic.gov.au/dpi/vro/glenregn.nsf/pages/glenelg_soil_map.*

[6] Bureau of Meteorology: Hamilton Airport – Station Number 90173.

[7] The mapping of EVCs must be taken as indicative, as spatial and ground observations show significant numbers of remnant River Red Gum on the area shown as Plains Grassland.

[8] *https://www.environment.vic.gov.au/biodiversity/bioregions-and-evc-benchmarks.*

2 METHOD

The aim was to provide an estimate of the carbon sequestration over the period 2006 to 2046 by trees planted at Jigsaw Farms (Figure 1) from 1987 to 2021, using the FullCAM model (2020 Public release version).

Figure 1. Location of Jigsaw Farms in south-west Victoria. The enterprise consists of two properties – Hensley Park (centre of map on Left) and Melville Forest to the north west.

Modelling of carbon stocks in woody vegetation using FullCAM[9] is carried out in carbon estimation areas (CEAs). These are areas with uniform site characteristics, are planted with the same mix of plant species, are established and managed under the same regime, have an area of at least 0.2 ha, and have forest potential. [Land has forest potential if the vegetation on the land includes trees that have the potential to reach 2 metres or more in height and provide crown cover of at least 20% of the land.][10] The key data required for modelling carbon sequestration in a CEA are the area established and the date of planting.

2.1 Mapping of tree plantings

Collection of this data started when Hugh Stewart and Rod Keenan visited Mark Wootton and Eve Kantor at Jigsaw Farms on 11-12 May 2022. They discussed farm management, the role of trees on the properties, and obtained mapped details of tree plantings established since the late 1980s.

There were two types of tree plantings at Jigsaw Farms – permanent revegetation with a mix of tree species and shrubs, and agroforestry plantings of eucalypt species managed for timber production.

Following the site visit, we made shapefiles for the tree plantings in Google Earth using the property maps for Hensley Park and Melville Forest. We prepared a list of CEAs showing species,

[9] The Full Carbon Accounting Model is a calculation tool for modelling Australia's greenhouse gas emissions from the land sector. FullCAM is used in Australia's National Greenhouse Gas Accounts for the land use, land use change and forestry sectors. Results from modelling are used to produce the annual totals for Australia's National Inventory Reports. *https://www.dcceew.gov.au/climate-change.*

[10] Carbon Credits (Carbon Farming Initiative) (Reforestation by Environmental or Mallee Plantings—FullCAM) Methodology Determination 2014, Compilation No. 2, 2018, Authorised Version F2018C00118 registered 26/02/2018.

method of establishment (planted tubestock or direct seeded), age, mapped area and 'stocked' area.[11] This data was cross-checked in follow-up site visits made on 8 August and 30-31 August 2023 and during further discussions with Mark Wootton. Paddock trees and 24 ha of remnant forest at Melville Forest were excluded from the analysis; collectively, paddock trees probably provide 1-2 per cent tree cover at Jigsaw Farms.

2.2 Modelling of carbon sequestration

We estimated carbon sequestration in the agroforestry and permanent revegetation plantings using the predictions from the FullCAM model (2020 Public release version). FullCAM has various calibrations to estimate forest growth and hence carbon sequestration to cater for different species, planting densities and planting configurations. The default calibration of 'Mixed species environmental planting temperate – Block planting' provides the most conservative estimate of forest growth. If a plantation species is planted, as in the case of agroforestry plantings at Jigsaw Farms, calibrations specific to these species can be applied which will result in a higher rate of carbon sequestration. We set up five models using different calibrations (Table 1).

Table 1. Models used to estimate carbon sequestration by trees planted at Jigsaw Farms.

Model	Tree planting type	Tree growth calibration
1	Permanent revegetation Agroforestry	'Mixed species environmental planting temperate – Block planting' for all CEAs (the default).
2	Permanent revegetation Agroforestry	As for Model 1, except that 'Mixed species environmental planting temperate – Belt plantings <1500 sph' was applied to eligible CEAs in permanent revegetation.
3	Permanent revegetation Agroforestry	As for Model 2. 'Plantation' calibration after Paul et al. (2022).
4	Permanent revegetation Agroforestry	As for Model 2. 'Plantation' calibration after Paul et al. (2022) adjusted using measurements of site-specific growth collected at Jigsaw Farms.
5	Permanent revegetation Agroforestry	Estimates from Model 2 adjusted using measurements of site-specific growth collected at Jigsaw Farms. As for Model 4.

All plantings were modelled with a start date of 1 July in the year the plantings were established. The model for each CEA was run from the planting date until 2046, using a modelling point that was in the approximate centre of the CEA. The details of the five models are provided below.

2.2.1 Model 1

Under the Methodology Determination we followed we initially modelled the permanent revegetation and agroforestry as 'Mixed-species environmental planting temperate – Block configuration'[12].

2.2.2 Model 2

Under the Methodology Determination, a 'belt' planting means a planting that is established in a belt configuration, follows landscape contours, or is arranged in a straight line, and is no more than 40 m wide. Plantings that do not meet these requirements are 'block' plantings. FullCAM has calibrations for belt plantings with <1500 stems per ha and belt plantings with >1500 stems per ha.

[11] 'Stocked area' was those parts of mapped areas that had achieved forest cover or had forest potential, as assessed from spatial imagery and some ground-truthing.

[12] Carbon Credits (Carbon Farming Initiative) (Reforestation by Environmental or Mallee Plantings—FullCAM) Methodology Determination 2014, Compilation No. 2, 2018, Authorised Version F2018C00118 registered 26/02/2018.

There are further calibrations for different establishment methods (the use of weed control and application of fertiliser). For Jigsaw Farms for Model 2, we used 'Mixed-species environmental planting temperate – Belt configuration, <1500 stems per ha (sph)' for those permanent plantings that met the requirements of a belt configuration.

In applying the calibration for the belt configuration, we applied the test for 'material competition' from adjacent trees specified in the Methodology Determination and adjusted where necessary the length of the belt to which we could apply the calibration. At Jigsaw Farms most of the material competition was caused by remnant River Red Gum trees.

At both Hensley Park and Melville Forest, 34 per cent of the area of permanent revegetation plantings were modelled using the calibration for belt configurations.

2.2.3 Model 3

For the Jigsaw Farms location, FullCAM had calibrations for three eucalypt plantation species but not for species established in the agroforestry plantings. We discussed this with a FullCAM expert[13] and developed an approach to model abatement in the agroforestry plantings, which led to the use of a user-defined calibration in FullCAM. This was based on recently published information that is being used in the recalibration of FullCAM for a new version expected to be released in 2023 (Appendix 1).

2.2.4 Model 4

We collected tree inventory data from the agroforestry plantings at Jigsaw Farms to improve the user-defined calibration we used in FullCAM. We did this by adjusting the tree growth calibration in FullCAM after comparing measured tree growth with growth predicted by FullCAM. Details of the method are provided at Appendix 2.

2.2.5 Model 5

In our analysis of carbon sequestration by permanent revegetation plantings at Jigsaw Farms, we considered the possibility that FullCAM underpredicted the actual rate of carbon sequestration. To test this, in April 2023 we collected field measurements of the growth of the permanent revegetation plantings including those that were direct seeded with high plant densities. The aim was to measure carbon stocks in the live aboveground biomass and compare the results with those predicted using the FullCAM model.

From a sample of permanent revegetation tree plantings 13 to 31 years of age at Jigsaw Farms, we found that FullCAM (2020 Public Release version) consistently predicted lower carbon stocks in the live above-ground biomass relative to estimates derived from field measurements. The results indicated that the measured carbon stocks were in the order of two times to four times those predicted by FullCAM – equivalent to 100% to 300% higher (Appendix 3).

Based on these findings, we applied a multiplier of two to the FullCAM carbon predictions for the permanent revegetation plantings that we assessed as being closed forest (i.e., having a crown cover >80%). For plantings established between 1987 and 2017 we did this from Google Earth imagery with ground-truthing in April 2023 of some plantings close to the lower bounds of the crown cover class of closed forest. We assumed that plantings established since 2017 would become closed forest.

2.2.6 Conversion of FullCAM predictions to carbon dioxide equivalents

FullCAM predicts the amount of carbon in trees (above-ground and below-ground components) and debris, as tonnes of carbon per hectare. We converted these results to tonnes of carbon dioxide equivalent per hectare – t CO_2-e/ha – using a multiplication factor of 44/12.

[13] Geoff Roberts, Mullion Group, 5 August 2022.

3 RESULTS

3.1 Areas of agroforestry and permanent revegetation

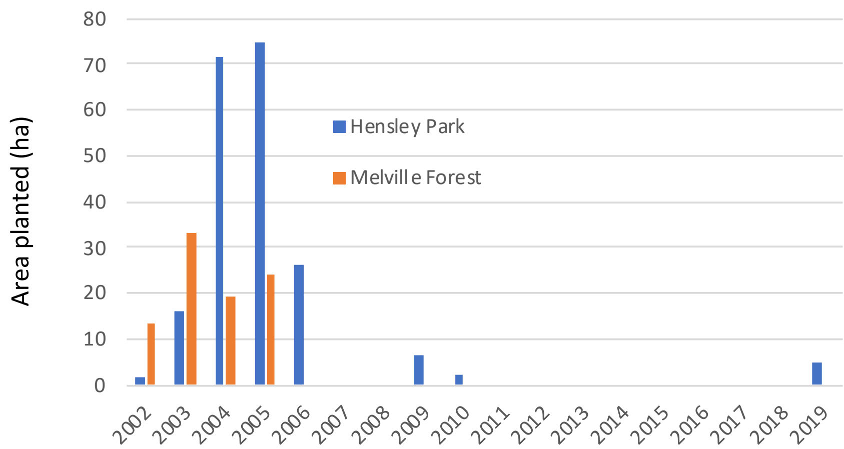
At Hensley Park, the tree plantings were mapped into 99 CEAs ranging in size from 0.2 ha to 25.0 ha, with a total area of 360.4 ha. At Melville Forest, there were 56 CEAs ranging in size from 0.5 ha to 21.0 ha, with a total area of 202.4 ha. Table 1 summarises the area of planted trees (i.e., the area of CEAs) and remnant forest at Jigsaw Farms. Maps of the CEAs are provided at Appendix 4.

Table 1. Area statement of tree plantings (stocked area) and remnant forest at Jigsaw Farms.

Property	Area (ha)	Proportion of property	Proportion of tree area
Hensley Park			
Property	2133		
Agroforestry	204	9.6%	57%
Permanent revegetation	156	7.3%	43%
Total area planted to trees	360	16.9%	
Melville Forest			
Property	1284		
Agroforestry	90	7.0%	40%
Permanent revegetation	112	8.7%	50%
Remnant forest	24	1.8%	10%
Total area of trees	226	17.6%	
Jigsaw Farms			
Property	3417		
Agroforestry	295	8.6%	50%
Permanent revegetation	268	7.8%	46%
Remnant forest	24	0.7%	4%
Total area of trees	587	17.2%	

The agroforestry plantings were predominantly Spotted Gum (72%) and Sydney Blue Gum (*E. saligna*) (19%); the balance was planted with Mahogany Gum (*E. botryoides*), Red Ironbark (*E. tricarpa*) and River Red Gum. The plantings were established from 2002 to 2019 (Figure 2).

Figure 2. Areas of agroforestry planted at Jigsaw Farms.



The agroforestry plantings were established by planting tubestock at a density of 1000 stems per ha. Stands were thinned mechanically by pushing and uprooting trees from about age eight years onwards, leaving about 500 stems per ha. Examples of the thinned stands are provided at Figure 3.




Figure 3. Agroforestry plantings at Jigsaw Farms. From top left, clockwise: Spotted Gum at Melville Forest, Spotted Gum at Hensley Park, Mahogany Gum at Hensley Park, Spotted Gum at Hensley Park. *Photos by Hugh Stewart.*

Areas of permanent revegetation were established by establishing a mix of trees and shrubs by planting tubestock or by direct seeding (Figure 4). Species established were indigenous but not necessarily from the local area. The previous owners of the Melville Forest property had participated in the Potter Farmland Plan[14] and had established 33 ha of permanent revegetation during the period 1987-1995. Since Jigsaw Farms acquired the property, the area of permanent revegetation has been more than trebled to a total of 112 ha as at 2022 – of the 79 ha of new plantings, 35 ha was direct seeded, some in blocks and others in belts. Prior to 1997, the proportions of trees and shrubs were 70:30; since then, they have been 60:40.

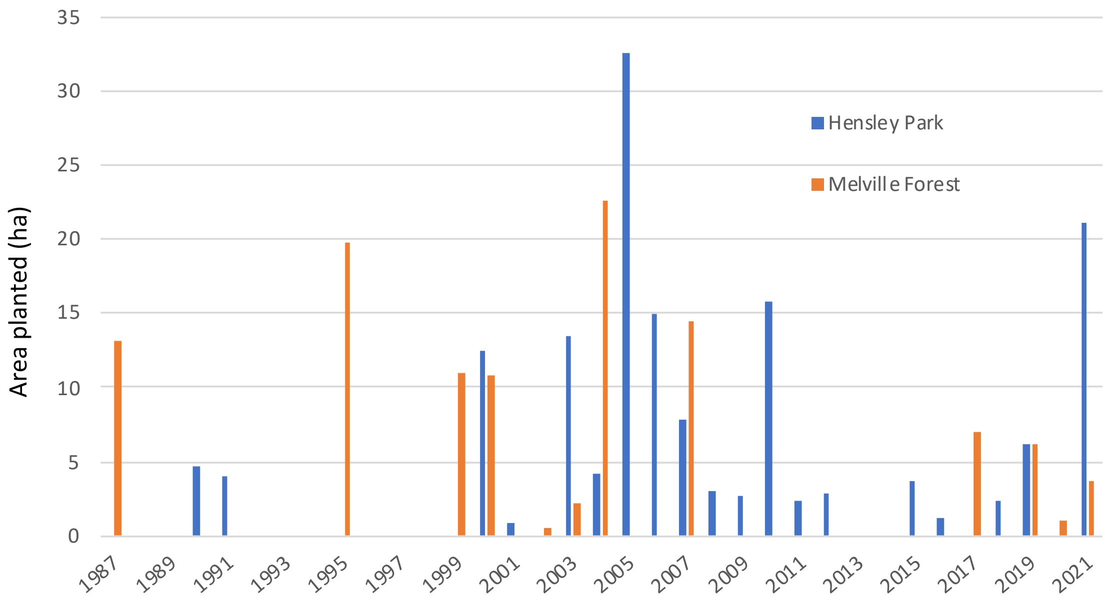
[14] The Potter Farmland Plan involved 15 demonstration farms set up in western Victoria in the mid-1980s by the Ian Potter Foundation. Farmers were given dollar-for-dollar support to redesign their farms according to land type.

Figure 4. Permanent revegetation at Jigsaw Farms.
From top left, clockwise: planted in 1995 at Melville Forest, Planted in 1999 at Melville Forest, planted at Hensley Park, direct seeded at Melville Forest, direct seeded at Hensley Park, paddock tree at Hensley Park.
Photos by Hugh Stewart.

At Hensley Park, nine ha of permanent revegetation had been established before the property was purchased by Jigsaw Farms in 1996. Since then, 147 ha of permanent revegetation has been established of which 50 ha has been direct seeded. The proportions of trees and shrubs have been 70:30.

The age profile of the permanent revegetation established from 1987 to 2021 is shown at Figure 5.

Figure 5. Areas of permanent revegetation established at Jigsaw Farms.



The total stocked area of agroforestry and permanent revegetation of 562 ha (plantings that had achieved forest cover or had forest potential) was less than the mapped area of plantings of 612 ha. The difference was due to dams embedded within mapped areas of tree plantings, waterways mapped as tree planting that were fenced and protected but only partially revegetated, and areas of tree planting that either failed or were unlikely to achieve forest cover.

3.2 Carbon sequestration

Annual carbon sequestration at Jigsaw Farms by planted trees from 2006-2046[15], expressed as tonnes of carbon dioxide equivalent per year (t CO_2-e/year), is shown for the five carbon sequestration models at Figure 6. The data is shown for five-yearly intervals from 2006-2046 at Table 2.

Sequestration varies over time driven by the episodic planting over the 34-year period from 1987-2021 and the pattern of tree growth that peaks at an early age and then slows as the trees fully occupy the site. Carbon sequestration by planted trees peaked at 11,434 t CO_2-e/year in 2011 (as estimated using Model 5). By 2021 it had declined to 6704 t CO_2-e/year. With no further planting, this rate is predicted to decrease to 2071 t CO_2-e/year by 2046.

The annual rate of sequestration at the two properties is shown at Figure 7. The patterns of carbon sequestration at Hensley Park and Melville Forest were similar, due mainly to a similar pattern of establishment of agroforestry plantings at both properties, particularly from 2002-2005 (Figure 2).

[15] '2006' is the 2005-2006 financial year.

Figure 6. Annual carbon sequestration from 2006-2046 by trees planted at Jigsaw Farms.

Table 2. Annual carbon sequestration in five-yearly intervals from 2006-2046 by trees planted at Jigsaw Farms.

Model	2006	2011	2016	2021	2026	2031	2036	2041	2046
1	1258	5762	3794	2936	2595	1966	1472	1125	883
2	1343	5890	3900	3098	2797	2022	1484	1122	875
3	1159	7550	5339	4533	3839	2829	2125	1642	1303
4	1358	10,314	7222	6088	4995	3706	2804	2180	1739
5	1784	11,434	8000	6704	5768	4416	3356	2605	2071

The relative contributions of agroforestry and permanent revegetation to the annual sequestration are shown at Figure 8. In terms of the annual rate of carbon sequestration, agroforestry plantings (295 ha at Jigsaw Farms) became the dominant type of planting in 2007 and was estimated to sequester substantially more carbon than the permanent revegetation plantings (268 ha at Jigsaw Farms) thereafter.

The relative proportions of annual carbon sequestration (Model 5) by the two types of plantings were:

	2006	2007	2011	2021	2046
Agroforestry	33%	54%	73%	71%	64%
Permanent revegetation	67%	46%	27%	29%	36%

On a unit area basis, the annual rate of sequestration (t CO_2-e/ha), based on the actual area of each type of planting at the time, was:

	2006	2007	2011	2021	2046
Agroforestry	2.3	6.9	28.7	16.1	4.5
Permanent revegetation	7.9	9.9	14.8	8.1	2.8

Figure 7. Annual carbon sequestration from 2006-2046 (Model 5) by trees planted at the Hensley Park and Melville Forest properties of Jigsaw Farms.

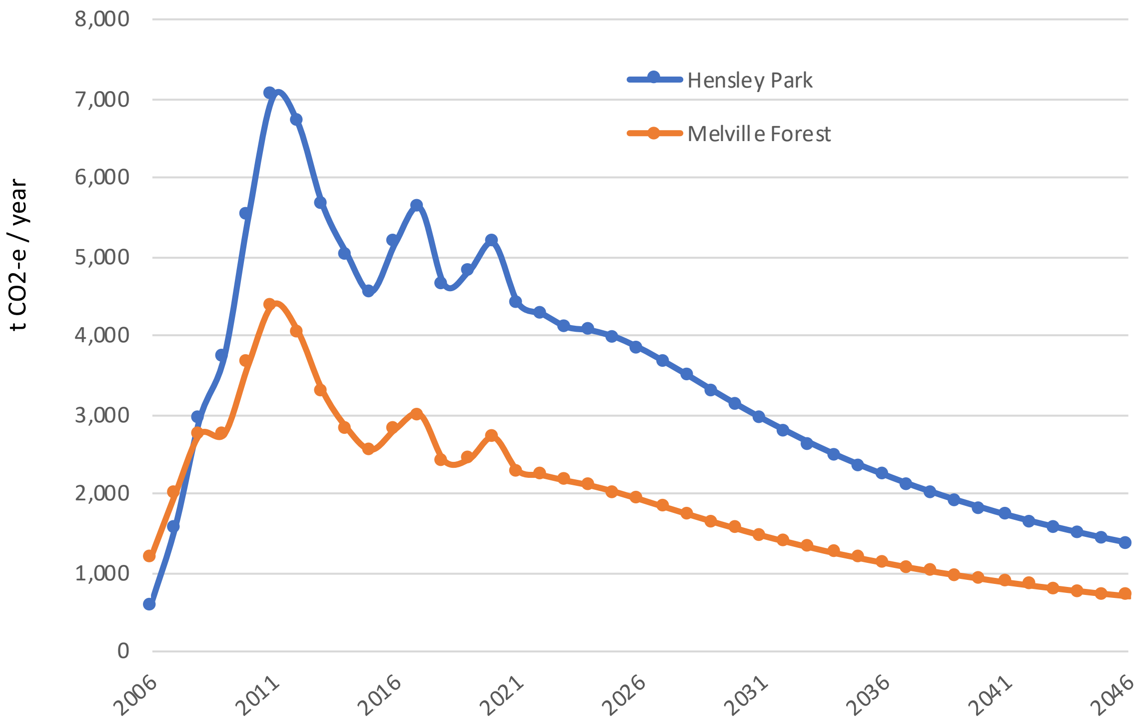
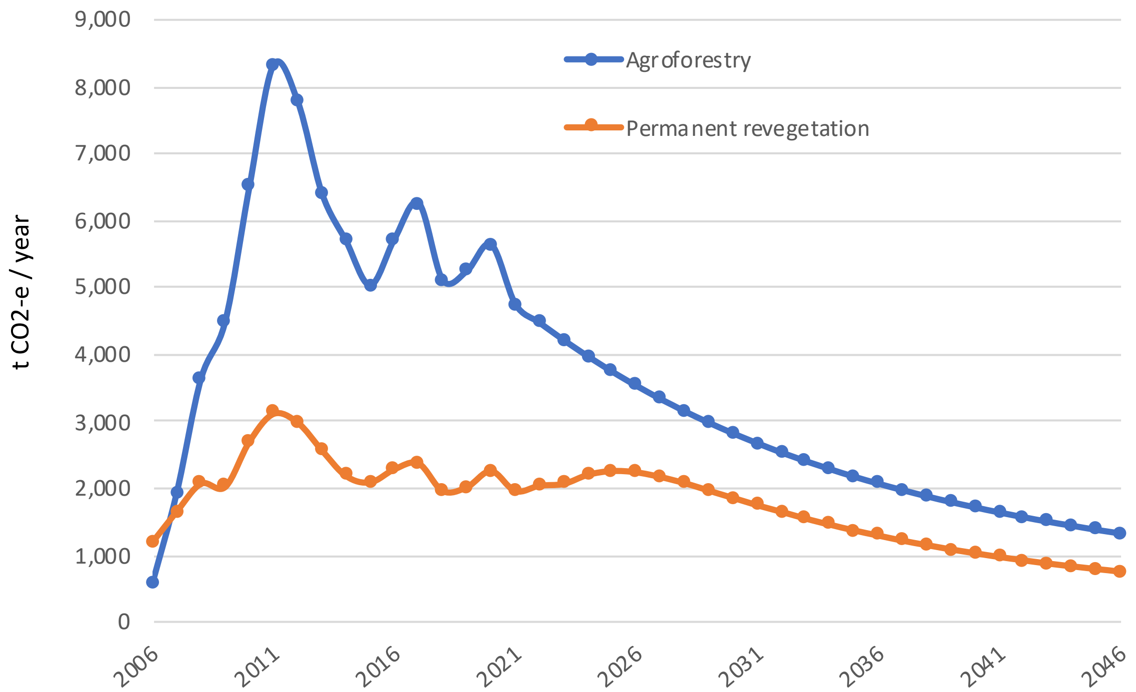
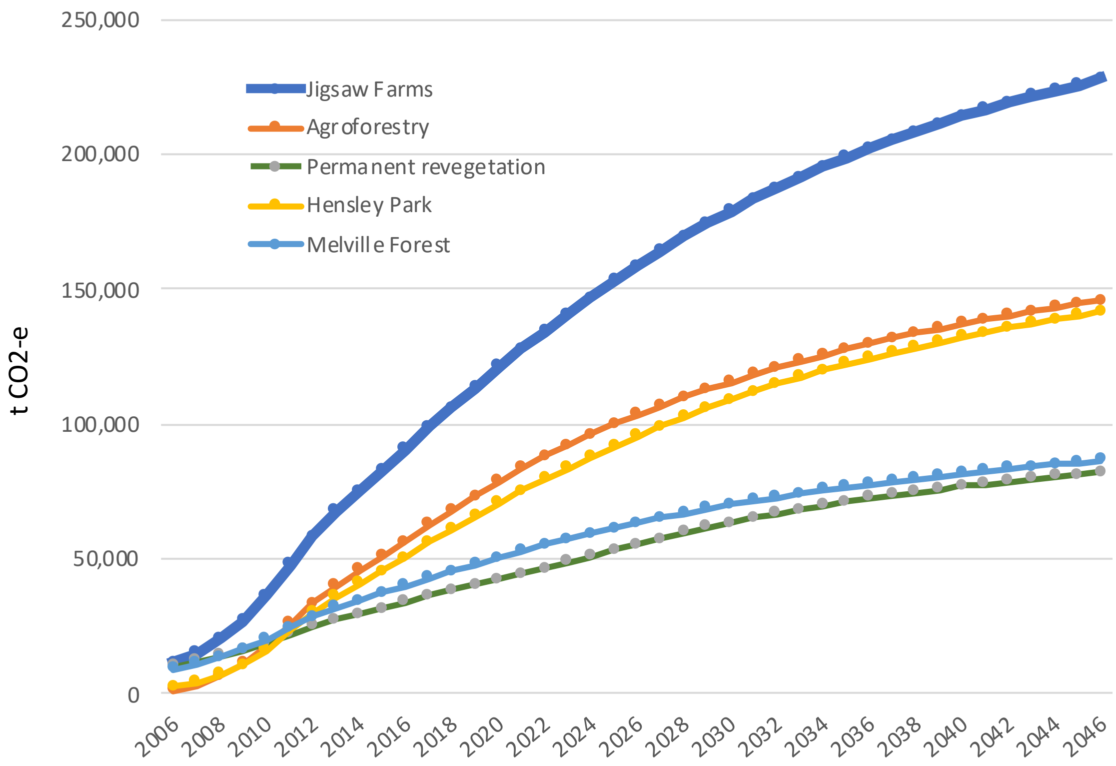


Figure 8. Annual carbon sequestration from 2006-2046 (Model 5) by agroforestry planted during 2002-2019 and permanent revegetation planted from 1987-2021 at Jigsaw Farms.



The cumulative carbon sequestration by trees planted at Jigsaw Farms from 1987-2021 is shown at Figure 9. In 2021, the total carbon sequestration of 128,000 t CO_2-e was made up of 75,170 t CO_2-e and 52,830 t CO_2-e at Hensley Park and Melville Forest, respectively; and 83,490 t CO_2-e and 44,510 t CO_2-e in the agroforestry and permanent revegetation plantings, respectively.

Figure 9. Cumulative carbon sequestration from 2006-2046 (Model 5) by trees planted at Jigsaw Farms from 1987-2021.



4 DISCUSSION

Trees sequester carbon at varying rates depending on the area planted, the planting configuration, the establishment and management methods, tree species and the climate and soils. Soil carbon can be increased with improved vegetation cover and input management. Rates of increase in tree and soil carbon (sequestration) slow over time as trees mature and begin to fully occupy planted areas and as the soil carbon holding capacity is reached.

At Jigsaw Farms the peak rate of carbon sequestration by planted trees occurred in 2011. After a period of steady decline, there were two more peaks in 2017 and 2020 caused by spikes in the areas of agroforestry planted in 2005 and 2010. After 2020 there was a slow, steady decline in the annual rate of carbon sequestration, which is what is expected in forest systems.

Climate and soils largely influence the underlying growth rates at a particular site. FullCAM predictions are heavily influenced by the parameter *M*, which defines the maximum above-ground biomass accumulation for undisturbed, mature native vegetation at the site in question. Across the two properties at Jigsaw Farms, there was considerable variation in the parameter *M*: the mean values of *M* for CEAs modelled, expressed as tonnes per hectare of dry aboveground biomass, were a mean of 74.1 (range 52.3-104.7) at Hensley Park, and a mean of 69.8 (range 60.3-93.5) at Melville Forest. Hence, the rates of sequestration predicted for some plantings of the same type and age at

Hensley Park, for example, varied by more than a factor of two when the inbuilt calibrations in FullCAM were used.

We compared the predictions by FullCAM for block and belt calibrations at sites with similar productivity, as estimated by the *M* parameter[16]. This allowed us to assess the difference in sequestration that can be achieved in belt plantings compared to block plantings. At peak growth, the annual rate of sequestration for the shelterbelts was nearly double that of the block plantings, but by about age 20 years, the annual rate of sequestration was similar for both types of plantings. Over a 30-year simulation period, FullCAM predicted that the cumulative sequestration for the shelterbelts would be about one-third more than by the block plantings, on a per ha basis.

Shelterbelts are clearly more efficient at accumulating carbon than block plantings under the calibrations in FullCAM. However, this result needs to be treated with some caution. In practice, the differential in tree growth and hence carbon sequestration between these two planting configurations will largely depend on the width of the belt. For example, a 10 m wide belt will have a higher proportion of 'edge' trees that will generally be larger than internal trees due to less inter-tree competition, than say a 20 m wide belt. Thus, in practice, the narrower the belt, the greater the expected differential between carbon sequestration per unit area when comparing belt configurations to block configurations.

Bennett et al. (2022) observed that differences between FullCAM predictions and field-based estimates of live biomass carbon stocks had tended to increase over time. They suggested many reasons for why FullCAM predictions of carbon stocks were consistently lower than those they estimated from field measurements. These included that most of the validation data for the FullCAM model have been from plantings less than about 20 years of age, and that longer-term carbon accumulation by environmental plantings is poorly quantified for temperate regions in Australia. On the other hand, they noted that allometric equations may be sensitive to overestimation of biomass in older plantings with trees with diameters greater than 50 cm. When we examined our data, we found that at the Jigsaw Farms site that had the biggest difference between measured and predicted carbon stocks (ratio of 6.8), there were several large eucalypts including one with a diameter of 59.5 cm. Removing that tree from the plot reduced the ratio to 4.5. This effect and other observations we made at Jigsaw Farms showed that eucalypts in permanent revegetation plantings were the dominant producers of biomass and hence carbon stocks.

It is difficult to compare our results with those of a previous study in which the carbon balance of the agricultural enterprises at Jigsaw Farms was calculated (Doran-Browne et al. 2018). In that study only the Hensley Park property was used. Both studies, however, found that the peak rate of carbon sequestration by planted trees occurred in 2011.

5 CONCLUSION

We provided an estimate of the rate of carbon sequestration and the carbon stocks from 2006-2046 in agroforestry and permanent revegetation plantings established from 1987-2021 on the Hensley Park and Melville Forest properties of Jigsaw Farms, using the FullCAM model (2020 Public release version).

Carbon sequestration by planted trees peaked at 11,434 t CO_2-e/year in 2011. By 2021 it had declined to 6704 t CO_2-e/year. With no further planting, this rate is predicted to decrease to 2071 t CO_2-e/year by 2046.

[16] *M* is the maximum aboveground biomass (t dry matter/ha) in undisturbed native vegetation.

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APPENDIX 1

Plantation calibration used in Model 3

For the Jigsaw Farms location, FullCAM had calibrations for three eucalypt plantation species but not for species established in the agroforestry plantings. We discussed this with a FullCAM expert[17] and developed an approach to model abatement in the agroforestry plantings, which led to the use of a user-defined calibration in FullCAM.

To develop the user-defined calibration, we used the calibration for Sugar Gum (*Eucalyptus cladocalyx*), a species with similar growth habits to eucalypts established in the agroforestry plantings at Jigsaw Farms. We then applied 'User Defined Growth Calibration Parameters for the Tree Yield Formula' in the Trees / Growth tab of FullCAM, as provided for in FullCAM Help under 'Calculation of *G* and *r* for plantation tree species'. The Tree Yield Formula (TYF) predicts yields of above-ground biomass (t dry matter/ha) in stands of trees. FullCAM allows users to define the parameters *G*, and *r* in the TYF, where *G* is the tree age of maximum growth rate (years), and *r* is the site-productivity-dependent, non-endemic species multiplier, which for tree plantations, is also influenced by *M*, the maximum above-ground biomass (t dry matter/ha) in undisturbed native vegetation.

Paul et al. (2022, Table 4) provided new recommended default TYF parameters for various tree species and categories of plantings. The data is being used to re-calibrate the TYF, and to expand the range of species, management regimes, and regions that can be modelled, for a new version of FullCAM expected to be released in 2023. We used the parameters for 'OtherEuc' that predominantly comprises the species *E. cladocalyx*, *E. camaldulensis*, *E. saligna/botryoides*, *Corymbia maculata*, and *E. pilularis*. For our FullCAM simulations, we used the *G* parameter of 8.002 for that group of species, and calculated *r* for each FullCAM plot as $r = \mathrm{Exp}(ar) \times M^{br}$, where *ar* and *br* are scaling factors given that each FullCAM plot has a unique value for *M*.

We checked that the age of the plantations we simulated fitted within the temporal domain of application of the TYF calibration, and that the spatial domain of application of the TYF was only applied to areas with *M* values between the minimum and maximum found within their respective calibration sites and thus, between the corresponding minimum and maximum $r \times M$ values, by reference to data in Paul et al. (2022, Tables 1, 5).

Having done the above, we then adjusted the relative allocations of yield of biomass to the various components of the biomass (stems, branches, bark, leaves, coarse roots and fine roots) at the Trees / Growth tab. Then we adjusted the turnover percentages (½ life years) at the Trees / Plant tab and the breakdown percentages (½ life years) at the Trees / Debris tab. Data for these adjustments was taken from the latest version of the Australian National Greenhouse Accounts (Australian Government 2022).

We noted that the '*FullCAM Guidelines – Requirements for use of the Full Carbon Accounting Model (FullCAM) with the Emissions Reduction Fund (ERF) methodology determination: Carbon Credits (Carbon Farming Initiative—Plantation Forestry) Methodology Determination 2022*' had detailed guidance on how to use the FullCAM 2016 model to calculate abatement under the '*Carbon Credits (Carbon Farming Initiative—Plantation Forestry) Methodology Determination 2022*'. This included an Excel calculator for *G* and *r* when modelling a forest of a certain species and region specified in the Methodology Determination. The species and region we were modelling was not included in the Methodology Determination. We believe that the approach we took, of applying adjusted *G* and *r* parameters to the FullCAM 2020 calibration, provided a reasonable approximation of the results we could expect from the impending release of a revised FullCAM calibration.

[17] Geoff Roberts, Mullion Group, 5 August 2022.

APPENDIX 2

Plantation calibration used in Model 4

Tree inventory data was collected from the agroforestry plantings at Jigsaw Farms on the 8th and 30-31st August 2022. Thirteen CEAs out of a total of 45 CEAs in the agroforestry plantings were sampled – seven at Hensley Park and six at Melville Forest covering stands 17-20 years of age. The inventory was a combination of point sampling to estimate the basal area of the stands and area-based plots to measure stocking and stand height. Plots 20 m x 20 m were established in an unbiased manner in each CEA. Basal area was measured at the centre of the plot using a prism (2-factor). The number of live trees in the plot was recorded, and stand height was measured. A total of 34 plots were assessed, with the following results (mean data):

CEA	Species	Age (years)	Stocking (trees/ha)	Basal area (m^2/ha)	Height (m)
Hensley Park					
2	*Corymbia maculata*	19	375	28.0	20.1
3	*Corymbia maculata*	18	300	23.0	19.8
4	*Corymbia maculata*	18	188	20.0	18.4
6	*Corymbia maculata*	18	238	18.0	18.2
8	*Corymbia maculata*	17	213	17.5	174
28	*Eucalyptus botryoides*	18	300	24.7	21.4
31	*Eucalyptus saligna*	17	279	14.0	17.5
Melville Forest					
1	*Corymbia maculata*	20	200	19.0	18.3
2	*Corymbia maculata*	19	225	16.7	18.2
3	*Corymbia maculata*	19	325	20.0	20.1
5	*Corymbia maculata*	18	225	22.3	23.9
10	*Eucalyptus saligna*	19	300	19.0	19.7
9	*Eucalyptus tricarpa*	19	275	24.0	21.7

The data was used to calibrate the FullCAM Tree Yield Formula used for the agroforestry plantings in Model 3 (described at Appendix 1) for the specific sites at Jigsaw Farms where the agroforestry was established.

To do that, we assumed that the parameter *G* (the tree age (years) of maximum growth rate) was correct for the sites measured, but that *M* (the maximum above-ground biomass (t dry matter/ha) in undisturbed native vegetation) was incorrect for the site. To correct *M*, we needed to adjust the parameter *r* (the site-productivity-dependent, non-endemic species multiplier).

Using the graphical data in Paul et al. (2022, Fig. S13 (d)) that plotted above-ground biomass (AGB) against stand basal area for stockings from 125 sph to 2000 sph, we used our measurements of stand basal area and stand stocking to scale the expected AGB for each CEA where we had collected inventory data. In every case, this was less than the AGB predicted by FullCAM. We then re-opened the FullCAM file for each of the 13 CEAs and adjusted the parameter *r* by iteration to achieve the expected AGB and used the results as the predictions of carbon sequestration in Model 4. For another 18 CEAs, we inferred basal area and stocking from the measured CEAs considering their age, management history and geographic relationship and adjusted the parameter *r* in FullCAM. For the remaining 14 CEAs we applied no adjustment because the stands had variable stocking, meaning that in Model 4 the carbon sequestration for these CEAs was estimated as for Model 3.

APPENDIX 3

Measured and predicted biomass and carbon in permanent revegetation at Jigsaw Farms

Introduction

FullCAM is an empirical model that predicts the accumulation of above-ground biomass in woody vegetation from which carbon sequestration is estimated. Data collection and research is ongoing to improve the calibrations in the model and hence the accuracy of these predictions (Roxburgh et al. 2019). Predicting biomass and carbon stocks is challenging given the many variables that influence tree growth and hence carbon sequestration. Concerns have been raised about the accuracy of FullCAM estimates for environmental plantings on farmland (e.g., Bennett et al. 2022).

This issue was assessed at Jigsaw farms in April 2023 in a supplementary study in which the carbon stocks in the live above-ground biomass of permanent revegetation plantings were measured and compared with those predicted by the FullCAM model (2020 Public release version).

Method

The permanent revegetation tree plantings established at Jigsaw Farms since 1987 had considerable variation in plant spacing, plant density and canopy coverage. Plantings sampled were 13 to 31 years old and were 'closed forest' (at least 80% canopy projection as assessed from spatial imagery in Google Earth)[18]. The most recent Google Earth imagery for Jigsaw Farms was from 2018. We ground-truthed plantings close to the lower bounds of the crown cover class in April 2023, and for plantings established since 2017 we assumed that they would become closed forest. Five sites were sampled at Melville Forest and six at Hensley Park. Six of the sites were established by planting seedlings (tubestock) and five were direct seeded. The planting configurations were belts <40 m wide (six sites) and blocks (five sites).

The sampling was guided by the method of Bennett et al. (2022) – sampling plots were randomly located belt transects 5 m wide and of variable length (11 m to 50 m) depending on the size and shape of the planting. At each plot, the stem diameter of all standing live trees that were at least 5 cm in diameter was measured and the species group was recorded. Field data was collected from 13-14 April 2023, and the sample plots were 1.3% of the area of the plantings assessed.

Above-ground, live biomass for each plot was estimated from stem diameter measurements using allometric models for each species group, following Paul et al. (2016). Model parameters are provided at Table 1. Biomass of Acacias was estimated using the 'Multi' model, and biomass of Casuarinas using the 'Other' model. All trees measured were within the respective domains of the allometric models.

Table 1. Coefficients for allometric models for above-ground biomass using a predictor of diameter (D) measured at either 10 cm or 130 cm height.

Model (domain in parentheses)	Diameter measurement	ln(*a*)	*b*	Correction factor
Eucalypt (D_{130} < 169 cm)	D_{130}	-2.016	2.375	1.0668
Multi (D_{10} < 62 cm)	D_{10}	-2.757	2.474	1.0775
Shrub (D_{10} < 50 cm)	D_{10}	-3.007	2.428	1.1281
Other (D_{130} < 102 cm)	D_{130}	-1.693	2.220	1.0436

[18] We used the three canopy classes from the National Forest Inventory 2018: 20-50%, Woodland; >50-80%, Open Forest; >80% Closed Forest (Australia's State of the Forests Report 2018, p. 48).

Biomass for each plot, estimated as tonnes per hectare of oven dry mass (t DM/ha), was converted to mass of carbon in the live above-ground biomass using a multiplication factor of 0.5. These results were compared with above-ground carbon in trees predicted by FullCAM for the age of the planting.

The FullCAM model (2020 Public release version) was run for each planting with a start date of 1 July in the year in which the plantings were established, and a modelling point at the approximate centre of the planting. The calibrations used were as for Model 2 – 'Mixed-species environmental planting temperate – Block configuration' or 'Mixed-species environmental planting temperate – Belt configuration, <1500 stems per ha (sph)' for those permanent plantings that met the requirements of a belt configuration.

Results

The measured above-ground biomass from which above-ground carbon was estimated in permanent revegetation plantings at Jigsaw Farms is shown at Table 2.

Table 2. Measured above-ground biomass and estimated above-ground carbon in tree plantings at Jigsaw Farms.

Planting ID	Age (years)	Area (ha)	Stocking (stems/ha)	Above-ground biomass (t DM/ha)	Above-ground carbon (t C/ha)
MF1995.1DS	27	1.8	1556	222	111
MF1995.2	27	2.4	650	194	97
MF1999.2DS	23	1.0	1418	296	148
MF2004.2DS	18	12.3	1240	154	77
MF2007.2	15	1.1	906	184	92
HP1999.2	31	1.4	1341	255	127
HP2003.1DS	20	4.5	1860	67	33
HP2004.3	19	0.9	1550	93	46
HP2005.2DS	18	2.6	759	96	48
HP2010.2	13	0.8	1000	242	121
HP2010.6	13	2.5	750	116	58

Planting ID: MF = Melville Forest, HP = Hensley Park, 1995.1 = area no. 1 in the 1995 planting year, DS = Direct seeded (otherwise planted with tubestock); 'Stocking' is the number of live trees and shrubs per hectare.

The mean tree density at the six sites planted with seedlings was 1033 stems per hectare, compared to 1366 stems per hectare in the five direct seeded sites. Eucalypts were half of all trees measured across the plots yet contributed three-quarters of the estimated carbon stocks.

FullCAM underpredicted the carbon stocks in the live above-ground biomass relative to the estimates derived from field measurements for all sites sampled (Table 3). The ratio of the measured estimates to the FullCAM predictions ranged from a factor of 3.0 to 4.7 across the five sites at Melville Forest, and from 1.9 to 6.8 across the six sites at Hensley Park. The site with the lowest ratio (1.9) had only 3% of eucalypts by number. For the sites planted with seedlings, the measured estimates and the FullCAM predictions of carbon stocks, expressed as a ratio, ranged from 1.9 to 6.8; for direct seeded sites, the range was 2.3 to 4.7.

Tree densities were about one-third higher at direct seeded sites compared to planted sites, but this did not lead to markedly different carbon stocks than on planted sites for plantings of similar age.

The belt plantings generally had higher densities of carbon than the block plantings – the range of measured above-ground, live carbon stocks was 92-148 tonnes per hectare in belts, compared to 33-77 tonnes per hectare for the block plantings.

Table 3. FullCAM predictions of carbon at 30 June 2023 in permanent revegetation tree plantings at Jigsaw Farms, and the ratio of measured carbon (from Table 2) to the carbon predicted by FullCAM.

Planting ID	Age (years)	Calibration	MaxBio (t DM /ha)	FullCAM output (t C/ha)	Measured C / FullCAM C
MF1995.1DS	27	B<1500	74	33	3.4
MF1995.2	27	B<1500	74	33	3.0
MF1999.2DS	23	B<1500	72	31	4.7
MF2004.2DS	18	E	69	19	4.0
MF2007.2	15	B<1500	68	25	3.7
HP1999.2	31	B<1500	60	27	4.8
HP2003.1DS	20	E	53	15	2.3
HP2004.3	19	E	92	25	1.9
HP2005.2DS	18	E	62	16	3.0
HP2010.2	13	B<1500	58	18	6.8
HP2010.6	13	E	90	27	2.1

Planting ID: MF = Melville Forest, HP = Hensley Park, 1995.1 = area no. 1 in the 1995 planting year, DS = Direct seeding (otherwise planted with tubestock).

Calibration: E = Mixed-species environmental planting temperate – Block configuration; B<1500 = Mixed-species environmental planting temperate – Belt configuration, <1500 sph. [sph = number of live trees and shrubs per hectare.]

Maxbio, a spatial layer in FullCAM, is the maximum above-ground biomass of undisturbed, mature native vegetation, excluding standing dead material, measured in tonnes per hectare of dry matter (t DM/ha).

'FullCAM C' is t C/ha of above-ground tree components.

Conclusion

From a sample of permanent revegetation tree plantings 13 to 31 years of age at Jigsaw Farms, we found that FullCAM (2020 Public Release version) consistently predicted lower carbon stocks in the live above-ground biomass relative to estimates derived from field measurements.

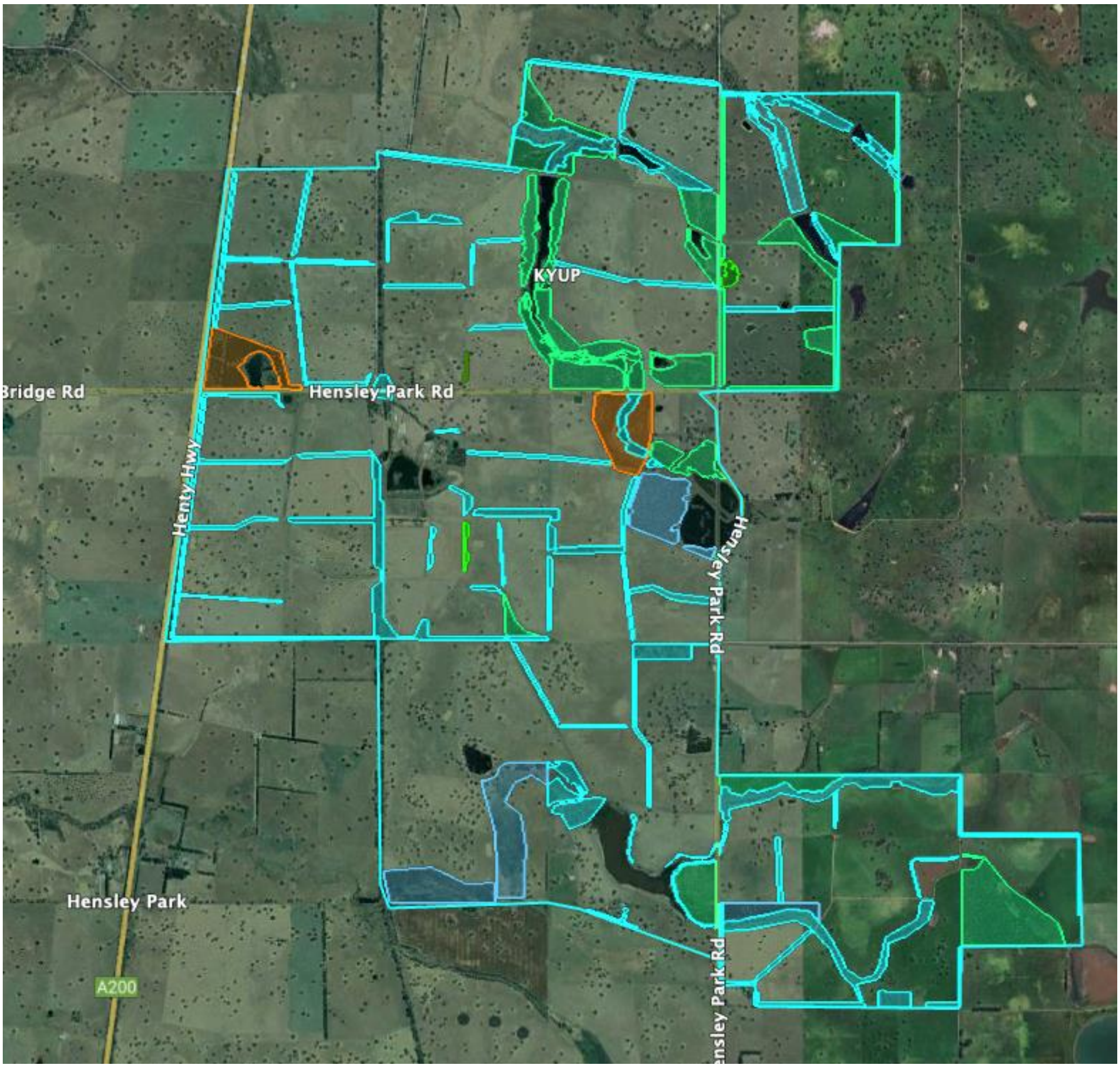
The results indicated that the measured carbon stocks were in the order of two times to four times those predicted by FullCAM (i.e., equivalent to 100% to 300% higher). Being conservative, the current FullCAM predictions of carbon stocks could be doubled for sites like those that were sampled.

The results also indicated scope to recalibrate FullCAM to improve its predictions of carbon stocks in mixed species environmental plantings dominated by eucalypts.

The results confirmed that the planting configuration that achieves the highest tree growth rates and hence carbon sequestration is narrow belts, due to such factors as the lack of external competition for a large proportion of the trees, and access to water and nutrients in adjacent fertilised pastures.

APPENDIX 4

Carbon estimation areas at Hensley Park [CEA labels removed to improve clarity]



Carbon estimation areas at Melville Forest