MURRAY BASIN
NRM CLUSTER

CLIMATE CHANGE IN AUSTRALIA

IMPACTS & ADAPTATION INFORMATION FOR AUSTRALIA'S NRM REGIONS

Identifying prospective areas for forest carbon farming

M.L. Cox[1], P. Polglase[2], L. Broadhurst[2], G. Forbes[1], D. Adams[1] C. Showers[1], J. Ha[1], V. Doerr[2], A. Reeson[2], C.S. Hawkins[2], K.I. Paul[2], J. Turner[2], D.F. Crawford[2], T. Jovanovic[2], T.J. Hobbs[2], K. Opie[2], J. Carwardine[2], A. Almeida[2]

1. DELWP
2. CSIRO

Citation

CSIRO and DELWP 2015, Identifying Prospective Areas for Carbon Farming, Impacts & Adaptation Information for Australia's NRM Regions: Murray Basin Cluster, CSIRO and DELWP, Australia.

Disclaimer

An Australian Government Initiative

Contents

We recommend using this approach to inform 'Step 5: Design interventions to maintain values' in The NRM Adaptation Planning Framework: six steps to transform NRM planning under global change (Ryan et al. 2016)

Summary

- This report explores the economic modelling of carbon farming projects and compares spatial patterns of carbon potential across the Murray-Darling Basin for both current and future climate
- Profitability for Carbon farming projects is dependent on the carbon market and the relative suitability of land for other more profitable farming practises
- Establishment costs of $1000/ha and a discount rate of 10% would allow profits in the Murray Basin NRM Cluster, given a $20/t CO_2-e carbon price.
- If establishment costs were $3000/ha and the discount rate was 10%, carbon farming profitability would be challenging in the Murray Basin.
- Highest carbon sequestration potential is in the southern and eastern sides of the Murray Basin and the lowest is in the northern and western regions
- The main driver for spatial patterns of carbon sequestration is the average rainfall pattern
- DELWP forest growth model results show that carbon sequestration rates could increase in a warmer climate
- There are risks to carbon farming related to the likely increased frequency of hot extremes
- A planning checklist for carbon farming has been included in this report to help farmers in their risk assessments

1. Introduction

This report aims to improve knowledge related to carbon farming for the Murray Basin NRM and CMA groups. This report indicates what areas of land in the Murray Basin might be potentially profitable for forest carbon farming. This report is designed to help the reader better understand the assumptions and input variables to which carbon sequestration predictions are sensitive and the extent to which those variables differ spatially, now and into the future. To that end, risks to carbon stocks and carbon farming ventures associated with climate variability are discussed. Several approaches have been used including computer model simulations of carbon sequestration, economic simulations and scientific literature reviews.

The main findings of the economic modelling are that an establishment cost of $1000/ha and a discount rate of 10% would be profitable in the Murray Basin, where the carbon price is at least $20/t CO_2-e. There is some uncertainty around the carbon price and the future carbon market and this is a potential problem as carbon farming has a long-term investment time-scale. Valuable farming land is not likely to be converted to carbon plantations unless the carbon price becomes much higher, as current farming profits would need to be forfeited. Carbon farming is more appealing on marginal farming land and there may be more incentive for farmers to enter aggregated carbon farming consortium projects.

The modelling of carbon sequestration across the Murray Basin indicates that the highest potential is in the southern and eastern regions. Average rainfall patterns correspond to the spatial variation in carbon sequestration, with high rainfall regions associated with high carbon sequestration. A secondary driver for carbon sequestration appears to be soil type and soil moisture. A large uncertainty in future climate projections is related to the prediction of rainfall, with climate models performing less well in this area. Under climate change, there are likely to be increased hot extremes, increased drought and associated bush fire risk. The requirements of carbon farming contracts are to replace carbon stocks which are damaged, so there are potential risks related to tree damage or mortality from bush-fire drought-related water shortages. Where climate projections for low and medium-high emissions were input to the DELWP forest growth model, carbon sequestration rates were higher when the simulation was started in 2050, relative to current conditions. The result for 2050 needs to be viewed in terms of the high uncertainty of rainfall patterns in these climate projections.

This report contains the results of forest growth modelling from two different models, CSIRO 3PG-2 and the Department of Environment, Land, Water and Planning (DELWP) 3PG+. In order to make a comparison between the carbon sequestration results, the CSIRO 3PG-2 and DELWP 3PG+ models are compared in terms of their model setup. The DELWP 3PG+ carbon farming sequestration results for several emission scenarios (low and medium-high) are presented using both a UK and an Australian climate model. The effect on carbon sequestration of planting year (current or future climate) is also investigated for forest growth modelling under various climate change scenarios.

Economic modelling by CSIRO, incorporating a range of hypothetical establishment costs and carbon prices is presented in this report. This includes predictions of which regions are profitable and an investigation of their sensitivity to a whole range of assumptions including acceptable profitability, growth rates of vegetation and changing carbon prices. The areas identified as being potentially profitable should therefore be seen only as regions of relative opportunity, to guide decision making. More detailed analyses of expected growth rates and economic returns might be warranted to verify the potential of predictions.

Current Carbon Farming Policy

The Emissions Reduction Fund (ERF) is the Commonwealth Government vehicle for Carbon Farming credits, replacing the Carbon Farming Initiative (CFI). The objective of the ERF is to help achieve Australia's 2020 emissions reduction target of 5% below 2000 levels by 2020 (http://www.environment.gov.au/climate-change/emissions-reduction-fund/about). One limitation for landowners with ERF is that the requirement is for a minimum of 2000 CO_2–e t/year over the life of the contract. This minimum requirement would only suit large projects, but for small projects it is possible for landowners to enter into contracts with carbon farming consortiums that aggregate small projects and apply for ERF funding. There are a range of options available to landowners for carbon farming including:

- Mallee plantings,
- environmental plantings, and,
- reforestation/afforestation.

Mallee plantings are for low rainfall areas (i.e. those below 600 mm) whereas 'environmental plantings' relate to native species planted on cleared or partially cleared land. Reforestation projects allow any plant species to be used except for species declared as "Weeds of National Significance" by the Commonwealth Government (http://www.weeds.org.au/WoNS/), to be planted on cleared land. To protect water security, plantings on land with greater than 600 mm annual rainfall must be a permanent environmental planting or a planting that addresses the mitigation of dryland salinity.

Making decisions regarding where and what to plant for carbon farming is, however, complex. Modelling can help to guide planning processes regarding where and how to invest for initiatives such as those funded by the ERF.

Modelling Background

The forest growth models used to guide these decisions are complex, use numerous variables and can make a large number of assumptions. Consequently, outputs from these models can vary widely depending on the variables and assumptions used. Typically, a model of a complex system uses research-based data of a physical system to create equations that describe the processes and interactions operating within that system. These equations are then combined into a mathematical model that is calculated at a specific grid resolution. These models also require inputs, such as climate and soil data, which come from physical observations. But modelling complex systems also requires many assumptions and can, in reality, only approximate the actual biophysical processes. This is especially so since many of the processes being modelled occur at a sub-grid scale. Figure 1 shows a flow chart of a typical biophysical forest growth simulation model. The forest growth models used here are therefore a complex system of assumptions and equations that can only approximate the actual living system. Outputs from a forest growth model include carbon stored and carbon sequestered.

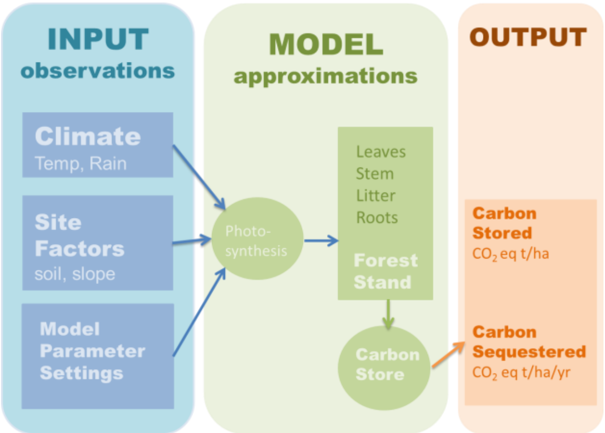


Figure 1. Flow chart of a typical carbon farming model.

Modelling Carbon in the Murray Basin NRMM Cluster

Two different forest growth carbon models, the CSIRO 3PG-2 and the DELWP 3PG+ models were used for this report.

Economic modelling by CSIRO incorporated a range of hypothetical establishment costs and carbon prices *to* generate predictions of potential profitability within the Murray Basin NRM Cluster. This analysis also scrutinised the sensitivity of the model to a range of assumptions including acceptable profitability, growth rates of vegetation and changing carbon prices. The areas identified as being potentially profitable using this model should therefore only be considered as regions of relative opportunity not as predictions of profitability. Consequently, more detailed analyses of expected growth rates and economic returns would be warranted in order to verify the potential of these predictions.

Forest carbon modelling using the DELWP 3PG+ model was investigated using a range of future climate projections to indicate how carbon sequestration might respond to predicted changes in climate within the Murray Basin NRM Cluster. The effect of planting year (current or future climate) was also investigated under these climate change scenarios.

Comparison of the CSIRO and DELWP forest growth models

The CSIRO and DELWP forest growth models were both derived from the 3PG model (Landsberg and Waring 1997), although both have subsequently been substantially changed. Initial modifications to the DELWP 3PG+ model included changes to the model parameterisations for soil water, soil evaporation, runoff and run on process, root zone salinity, shallow groundwater source and canopy conductance (DSE 2007). Further modification of the model parameterisations included changes to the water balance, groundwater recharge, soil nutritional status, litterfall, root biomass moisture transfer, foliage-stem and root allocation (Feikema et al. 2010, Morris 2003). Although growth in the DELWP 3PG+ model is dependent on soil moisture, there is currently no capacity to include groundwater in this model. Calibrations for plant growth and biomass allocation were made using direct measurements from Victorian sites for selected Eucalyptus species, including *E. globulus*, *E. grandis*, *E. camaldulensis*, *E. obliqua* and *E. cladocalyx*.

Changes to the CSIRO 3PG-2 model included improvements to the modelling of understorey transpiration, growth responses to soil water stress and improvements to water balance and biomass partitioning (Almeida et al. 2007). The number of rain days in a month was also taken into account in the monthly time step for water balance. The understorey was modelled separately from the forest prior to and after canopy closure in terms of exposure to direct sunlight and water interception. Water stress was determined by the amount of water in a zone surrounding the roots and this is altered as the plant grows.

There are considerable differences between the CSIRO 3PG-2 and DELWP 3PG+ forest growth models and consequently the outputs produced in this report. Due to data availability the CSIRO modelling could be undertaken across the whole of the Murray basin NRM Cluster whereas the DELWP model can currently only incorporate data from Victoria. Nonetheless, both modelling approaches were used for this report to show the different types of forest growth modelling that are available and the types of outputs that these can provide. The CSIRO 3PG-2 was modelled and calibrated for a generic environmental plantings group that is representative of actual native mixed-species sites made up of eucalypts, acacias and other shrubs (Paul et al. 2013). In contrast, the DELWP 3PG+ model was simulated for Ecological Vegetation Classes (EVC) defined for common floristic, structural and ecological features to capture the variation in biodiversity across Victoria. The DELWP EVC classes modelled were based on a generic eucalypt species and vary in the parameters for root depth and root growth rate. The CSIRO 3PG-2 model used current climate variability while the DELWP 3PG+ model used future climate projections. Table 1 gives an overview of the differences in inputs such as climate and soil data across the two models and Table 2 gives a comparison of model calibrations, parameterisations and settings. Areas of the models which are compared include plant species calibration, the planting types used, forest management approximations, forest growth assumptions, model time-steps and how soil carbon was treated. The differences between these models are important when comparing the outputs. Changes in the level of carbon dioxide is something that could impact on forest growth in the future but it is not yet possible to include this variable in either of the carbon models used in this report.

Table 1. Comparison of inputs to CSIRO 3PG-2 and DELWP 3PG+ forest growth models.

Variable	Model	Description	Reference
Climate data	CSIRO	Historic average monthly climate data sourced from Scientific Information for Land Owners (SILO) data drill datasets with a grid of 0.05◦ x 0.05◦ resolution (about 5km x 5km)	Polglase et al. 2013, Jeffrey et al. 2001
	DELWP	Future climate projections at 0.05◦ degree spacing with daily temporal resolution: 1. CSIRO MK3.5 2. UKMO-HadCM3 for SRES scenarios B1 and A2	CSIRO – Gordon et al., (2010), UKMO - Stott et al., (2000)
Soil data	CSIRO	Spatial soil information was sourced from the Digital Atlas of Australian Soils mapping (1:500k). Soil Hydrological parameters were sourced from McKenzie's interpretations with additional data supplied by Gallant.	Northcote 1968, McKenzie 2000, Gallant 2003
	DELWP	Spatial soil information was sourced from the Land systems of Victoria mapping (1:250k) . Soil Hydrological parameters were sourced from McKenzie's interpretations of the Australian Soil Atlas with modifications by Carl Smith.	McKenzie 2000, Smith 2002
Soil fertility and moisture	CSIRO	Monthly soil moisture is calculated from a single soil layer, soil-water-plant interaction model. Sites were assigned a fertility rating (*FR*) based on a decision tree	Polglase et al. 2013
	DELWP	Daily soil moisture is calculated from a multi layered cascading bucket soil water plant interaction model.	Feikema et al., 2010, DSE 2007

Table 2. Comparison of model approximations in CSIRO 3PG-2 and DELWP 3PG+ forest growth models.

Variable	Model	Description	Reference
Model Calibration	CSIRO	Calibrated for environmental plantings at 53 Australian sites	Polglase et al. 2011
	DELWP	Calibration using direct measurements and biomass studies for selected Eucalyptus species in Victoria	Feikema et al. 2010
Planting Type	CSIRO	Environmental Plantings	Paul et al., 2013
	DELWP	Location specific EVC groupings represented by a generic Eucalypt species with variation for root depth and growth rate across group	Feikema et al. 2010
Forest management	CSIRO	Average stock approach for forests with short rotations	Polglase et al. 2008
	DELWP	None	DSE 2007
Understorey/ Overstorey	CSIRO	Overstorey and understorey	Polglase et al. 2013
	DELWP	Overstorey	Feikema et al. 2010
Forest growth/decline	CSIRO	20 year growth modelled then 20 year decline factor of 0.7 used	Polglase et al. 2013
	DELWP	80 year growth and therefore no decline	Pers. comm., Charles Showers
Soil carbon modelling	CSIRO	Changes in soil carbon are not included	Polglase et al. 2008
	DELWP	Mass of carbon in the soil is modelled including decay of plant litter	DSE 2007
Model time-step	CSIRO	Monthly time-step	Polglase et al. 2008
	DELWP	Daily time-step for water balance, otherwise monthly	Feikema et al. 2010

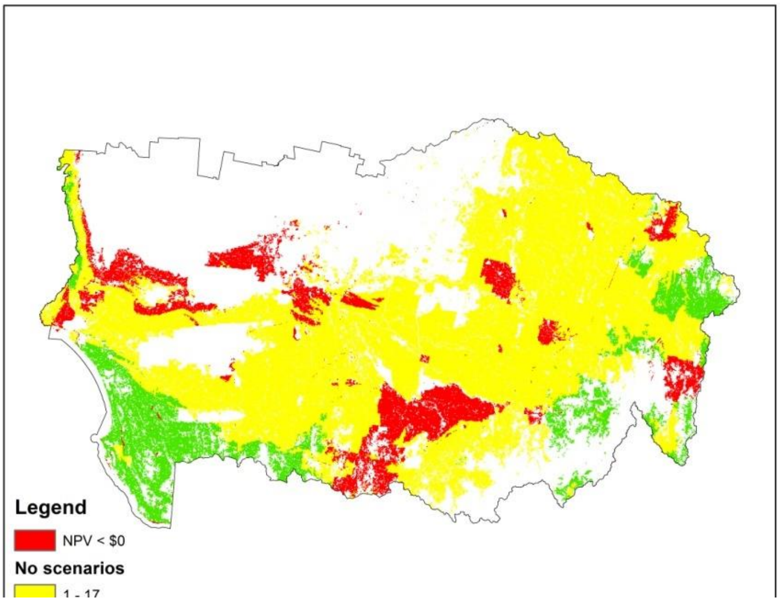
2. Areas of Economic Opportunity (CSIRO 3PG-2 model)

The maps produced here by the CSIRO 3PG-2 model were generated using previous national scale analyses of the economic viability of forest carbon farming (Polglase et al. 2011). They are based on environmental plantings of Australian native mixed species typical of those that would be established to enhance biodiversity. The Net Present Value (NPV) of carbon farming was calculated for every square km, based on the estimated growth rates of plantings and hence of carbon sequestration. Various hypothetical carbon prices ($5-50 per tonne of CO_2), establishment costs ($1,000 or $3,000 per ha) and financial discount rates (1.5, 5 or 10%) were modelled. Discount rates are based on future changes in earnings from the project and more information on the methodology is given in Polglase et al. (2013). The opportunity cost is the financial amount forfeited by making an alternative decision, or in this case changing the land use. The opportunity cost was taken as the land value which was estimated from 2009 local government area data. For example, the value of an area of farming land that will be converted to a carbon farming plantation represents the amount that is forfeited by the change in land-use.

Rates of carbon sequestration were spatially modelled and calibrated against measurements taken from environmental plantings across southern Australia. There is no single 'correct' scenario for these predictions with the most appropriate set of assumptions dependant on user-defined criteria and market conditions (most particularly, current and future carbon prices). Here, we extracted the Murray Basin NRM Cluster from the national layers and overlaid 42 scenarios for NPV calculations to identify which areas were most prospective for carbon farming in a relative sense. That is, the purpose was not to suggest which areas are or will be profitable but rather, to identify which areas have more potential in terms of economic viability when compared with other areas.

The results for each square km from each of the 42 scenarios were categorised as being profitable (NPV >0) or not (NPV <0). The 42 layers were then stacked upon each other and the number of profitable counts recorded for each square km. A single map was then generated (Figure 3) to indicate the frequency with which areas were 1. never profitable (red), 2. of medium profitability (yellow) or 3. of highest profitability (green). An interesting comparison with these compiled scenarios is if we consider just one combination of variables that might be considered to be 'plausible' under current market conditions. For example, using a $1,000/ha establishment cost, a carbon price of $20/t CO_2 and a 5% discount rate our modelling predicts that very few areas are likely to be profitable in the Murray Basin NRM Cluster (Figure 4). It then follows that the profitable yellow and green areas shown in Figure 3 are for scenarios that have relatively high carbon prices, or use a discount rate of *1.5%.* If a more commercially-focussed and conservative scenario that includes a discount rate of 10% and an establishment cost of $3,000/ha is used we find that no areas in the region were predicted to be profitable until very high carbon prices were reached.

Predicting areas of economic opportunity are naturally sensitive to many of the main assumptions used in the model. Polglase et al. (2011) provide a complete picture of examples of the sensitivity of assumptions to model results (https://publications.csiro.au/rpr/download?pid=csiro:EP113280&dsid=DS6) so here we summarise some of the main factors that have the largest impact on the model outputs. Figure 5 shows the



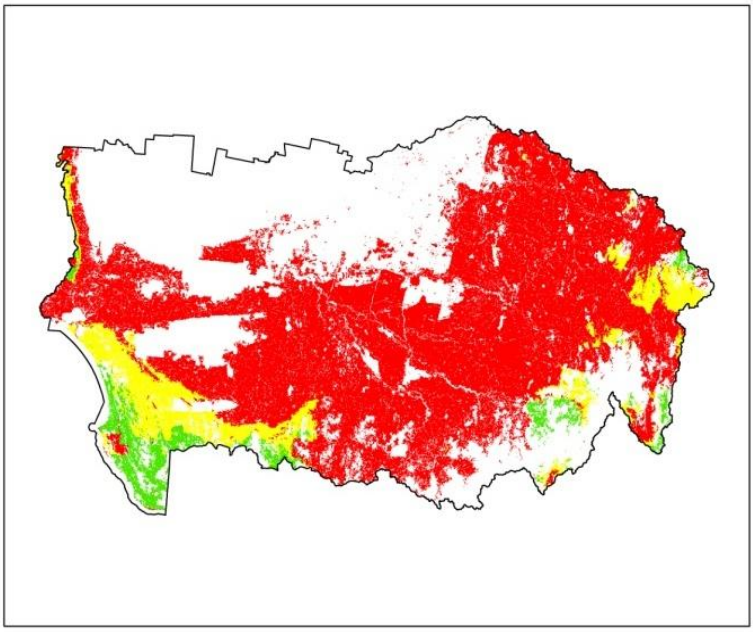


Figure 3. Results for the Murray Basin NRM Cluster from overlaying Scenarios 1-42 from the analysis of Polglase et al. (2011) in which establishment costs, carbon price, and financial discount rate were all varied. Red indicates areas that were not profitable (NPV<$0, 8 scenarios), yellow indicates scenarios of medium profitability (17 scenarios) and green indicates areas of highest profitability (17 scenarios).

Figure 4. Results for the Murray Basin NRM Cluster from a single scenario which has $1,000/ha establishment cost, 5% discount rate and carbon price of $20/t CO_2. Red indicates areas that were not profitable (NPV<$0, 8 scenarios), yellow indicates scenarios of medium profitability and green indicates areas of highest profitability.

total area of opportunity versus the carbon price for an establishment cost of $1000 and $3000, with a variety of discount rates. The calculations were made over the national scale and the results are equally applicable to regional scale predictions. The cost of establishing plantings is critically important and especially at a commercial discount rate (10%). For example, when an establishment cost of $3000/ha is used very few areas are predicted to be economically viable at a 10% discount rate regardless of carbon price. When an establishment cost of $1000/ha and a 10% discount rate is applied, areas only become profitable once a carbon price of $20/t CO2-e is reached. Notably, for the less conservative assumptions of $1000/ha and a 5% discount rate, areas are generally not profitable until a carbon price of $10/t CO2-e is reached. Generally, these results suggest that for forest carbon farming to be profitable, establishment costs should be kept to a minimum and that the current and potential carbon price have a high bearing on future profitability.

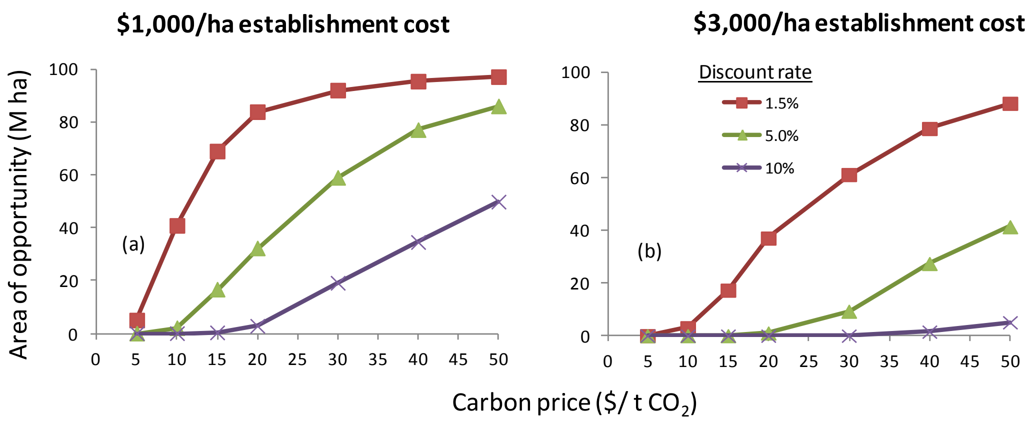


Figure 5. Results from a national analysis (Polglase et al. 2011) in which total area of opportunity (M ha) was identified depending upon different assumptions of establishment cost, discount rate and carbon price.

3. Carbon farming under future climates (DELWP 3PG+ model)

A range of forest growth model simulations were performed using the DELWP 3PG+ model to investigate the variation in the carbon sequestration results when different inputs, time-scales or model settings are used. These simulations were related to the: i) Ecological Vegetation Class (EVC) used for carbon farming; ii) variation found using a range of future climate projections and iii) difference found where the year of planting was changed. Forest growth was modelled for Victoria where the land use of cropping/grazing was replaced by a specific EVC type representing the new land use of carbon farming. The difference in carbon sequestration predictions for the DELWP 3PG+ forest growth model was investigated using climate projections from the CSIRO Mark 3.5 model (referred to as Mk 3.5, Gordon et al., 2010) and the UK Meteorological Office HadCM3 model (referred to as UKCM3, Johns et al., 2003).

The UK HadCM3 climate prediction model (http://www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadcm3) was chosen as it is a well-regarded model and the CSIRO model was chosen as it is known to perform well for Australian climate.

The climate projections used in the modelling are based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) low (B1) and medium-high (A2) emissions scenarios. Figure 6 shows how these SRES scenarios relate to the Representative Concentration Pathways (RCPs) outlined in the Murray Basin Climate Change Report (http://www.climatechangeinaustralia.gov.au/media/ccia/2.1.5/cms_page_media/172/MURRAY_BASIN_CLUSTER_REPORT_1.pdf).

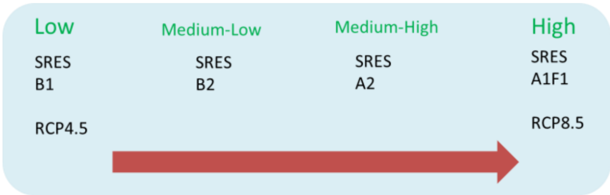


Figure 6. Comparison of the SRES and RCP climate projection emission scenarios

Evaluation of Climate Projections

A survey of GCM evaluation studies for the Murray Basin Region including a downscaling study for Wagga Wagga is discussed here, to give a context of how the climate projections used in the forest growth modelling fit into a climate futures framework (http://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-futures-tool/introduction-climate-futures/). The climate projections for HADCM3 and Mk3.5, fit into the 'hot' category, with relatively large reductions in rainfall. This is based on calculations of the changes in precipitation and temperature for future versus current climate, relative to various other models, for a range of emissions scenarios including B1 and A2.

Both HADCM3 and Mk3.5 were selected as part of a 'Hot' climate projections group of models for Australian regions. The study by Watterson surveyed a group of 23 CMIP3 global climate models using the A1B emissions scenario and found a subset of these models which represented high warming or hot climate projections with a positive PID index (denoted as group HP). The Pacific Indian Dipole (PID) is a dipole of sea surface temperatures (SSTs) in the western Pacific relative to SSTs in the eastern Indian Ocean. Watterson (2012) found that the PID was correlated with precipitation in regional VIC, with a score of -0.7. The HP sub-grouping of models included both the HADCM3 and the Mk3.5 models and the change in regional precipitation and temperature for this

Region	ΔT	ΔP
MDB	3.8	-18
VIC	2.8	-19
AUS	3.8	-21

Table 3. Regional mean changes for the Murray Darling Basin (MDB), Victoria (VIC) and Australia (AUS) for changes in annual temperature T(K) and precipitation P(%) over the 21st century under the A1B emissions scenario for sub grouping of 'High warming' or 'Hot' global climate models and positive Pacific-Indian dipole index (adapted from Watterson 2012).

Variable	Region	Mean	SD	Min	Max
δT	**AUS**	1.21	0.16	0.91	1.49
δT	**MDB**	1.17	0.19	0.80	1.51
δP	**AUS**	-3.5	5.9	-17.2	4.6
δP	**MDB**	-3.5	6.3	-19.7	7.7

Table 4. Statistics of the standardised changes (per degree of global warming) over the 23 models in annual temperature (T) or rainfall (%) for the mean, standard deviation (SD), maximum and minimum (adapted from Watterson 2012).

group is shown in Table 3. The standardised change in precipitation and temperature for 2100 relative to 2000 for the overall group of 23 models is shown in Table 4. If the results for the subgroup HP are compared to the overall results, we see that the rainfall decrease for the HP group is larger relative to the mean change in rainfall for all models and there is a large standard deviation of about 6mm for both regions. There is more certainty for temperature, with a standard deviation of 0.19 for the MDB region and the mean temperature change for all models is considerably less than the HP group.

A study undertaken for the Murray Darling Basin, which included the UKMO HADCM3 model, found that this model predicted a significant reduction in future rainfall. The HADCM3 model was evaluated by Smith and Chandler (2010) and was judged to provide good representation of Australian rainfall and the ENSO climate signal. In the same study, the percentage error for present day annual average rainfall (1971-2000) over the Murray Darling Basin (MDB) region was found to be 20% for the HADCM3 model, relative to observations. Many other GCMs in the survey performed worse in the comparison with past precipitation observations. Various criteria were applied to assess the group of models and the HADCM3 model was chosen as one of the best models. The simulated percentage change in MDB annual average rainfall (2070-2099) versus (1971-2000) was found to be -15% for the HADCM3 model. The mean change in precipitation was -3% with a standard deviation of 15%, so there was considerable uncertainty for rainfall projections for 2070-2099 across the study which included a suite of 22 global climate models. Future climate projections of rainfall have greater uncertainty across GCMs, relative to temperature.

The CSIRO Mk3.5 model has been studied in a statistical downscaling for the town of Wagga Wagga for the emission scenarios of A1B, A2 and B1 (Liu and Zuo 2012). Table 5 shows a summary of the change in temperature and precipitation in 2050 (2041-2060) over the baseline (1960-1999) with a comparison of the mean, standard deviation (SD) and the range in results for all models. The precipitation changes show a difference between the A2 and B1 emissions scenario, with a smaller reduction in precipitation for the A2 scenario. The reduction in precipitation for the B1 and A1B scenarios were similar to the HP group results. The change in temperature predicted for Wagga Wagga was about 2 degrees and this was close to the average for all 9 GCMs in the study. For the Mk3.5 model the reduction in precipitation was larger compared to the mean

Variable	Category	A1B	A2	B1
ΔT	CSIRO-Mk3.5	2.3	2.2	2.1
ΔT	All models (range)	21 to -19	7 to -13	7 to -19
ΔT	mean	2.1	2.0	1.8
ΔT	SD	0.6	0.3	0.5
ΔP	CSIRO-Mk3.5	-19	-13	-19
ΔP	All models (range)	1.3 to 3.3	1.5 to 2.3	1.2 to 2.7
ΔP	mean	1.1	-3.3	-3.1
ΔP	SD	14	6.5	10.2

Table 5. Changes in mean temperature and precipitation in 2050 (2041-2060) over the baseline (1960-1999) at Wagga Wagga, NSW (taken from Liu and Zuo 2012).

result for all models. As the reduction in precipitation was similar for both the Mk3.5 and HADCM3 models, we can assume that both models showed greater reduction in precipitation than an average GCM.

Climate Change Forest Growth Modelling Results

The climate projections predict a warmer climate in 2050, relative to 2015. The DELWP 3PG+ carbon forest growth model was started in both current (2015) and future (2050) climate conditions to investigate the resulting differences in carbon sequestration.

The DELWP 3PG+ model is parameterised with a selected group of Victorian EVCs (Table 6). The main difference between the EVC groups is the variation in root depth and root growth rate. Existing forest communities across Victoria have been matched to an EVC class and all of these model settings were retained in the simulations. For example, the vegetation type 'Box Ironbark Forest' is modelled as EVC Dry Forest (EVCDF). Forestry, grazing, pasture and cropping land uses in the DELWP 3PG+ model had no EVC class assigned. These land uses were converted to a

Category	Vegetation Type
EVCDF	dry forest
EVCGF	grassy forest
EVCHW	heathy woodland
EVCGW	grassy woodland
EVCWW	wet/damp/rainforest
EVCMA	Mallee
EVCST	scrub/thicket/shrub
EVCHT	heathland
EVCGR	grassland

Table 6. EVC groupings in DELWP 3PG+

broad carbon farming land use and an EVC class was assigned. Forest growth simulations were run for the carbon farming land use with the EVCDF, Mallee EVC (EVCMA) and the Wet/damp/rainforest EVC (EVCWW). Forest growth simulations using EVCDF for the carbon farming land use were used for the statistical

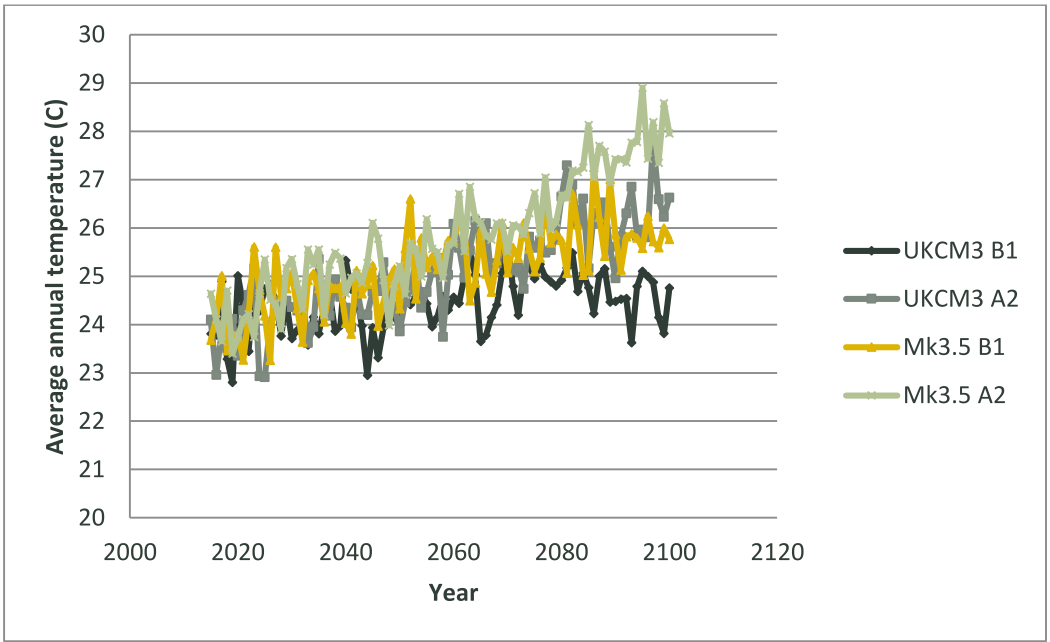


Figure 7. Comparison of the average maximum temperature for Victoria for the climate projections for UKCM3 B1 (low), UKCM3 A2 (med.-high), Mk3.5 B1 (low) and Mk3.5 A2 (med.-high) over the years 2015-2100.

analysis, as this EVC could be located across all rainfall zones of Victoria. EVCWW is not an EVC class suitable for low rainfall areas of the Murray Basin NRM Cluster, however, it is interesting to compare the spatial variation in carbon sequestration for EVCWW versus EVCMA. For example, the modelling of EVCWW over the Murray Basin NRM Cluster shows how an EVC class which requires significant rainfall might respond in a warmer and possibly drier climate. In contrast, the modelling of EVCWW allows us to observe the response of a more rain-dependent forest-type to variation in rainfall over future climate projections.

We have assumed for this model that farming practices may become less practical under a warmer and dryer climate and that with a reasonable price on carbon, carbon farming would become a more financially sound option. Irrigated land uses were also modelled as carbon farms as we assumed that water shortages due to drought may prevent irrigation practices. The output was masked using the PLM25 (Crown land, Parks and reserves) layer and land uses such as urban/rural residential, poultry, dairy, greenhouses, piggeries, roads and lakes. A summary of the average climate projections across Victoria for maximum temperature is shown in Figure 7. When comparing the four climate projection scenarios, we see that the highest temperatures predicted are for the climate projection of Mk3.5 A2 (dark green line) and the lowest are for UKCM3 B1 (black line). The projection for Mk3.5 B1 (yellow line) is similar to that for UKCM3 A2 (light green line). The change in average precipitation for the climate projections for VIC are shown in Figure 8. The main trends indicated here are a greater precipitation variability for all projections after 2040.

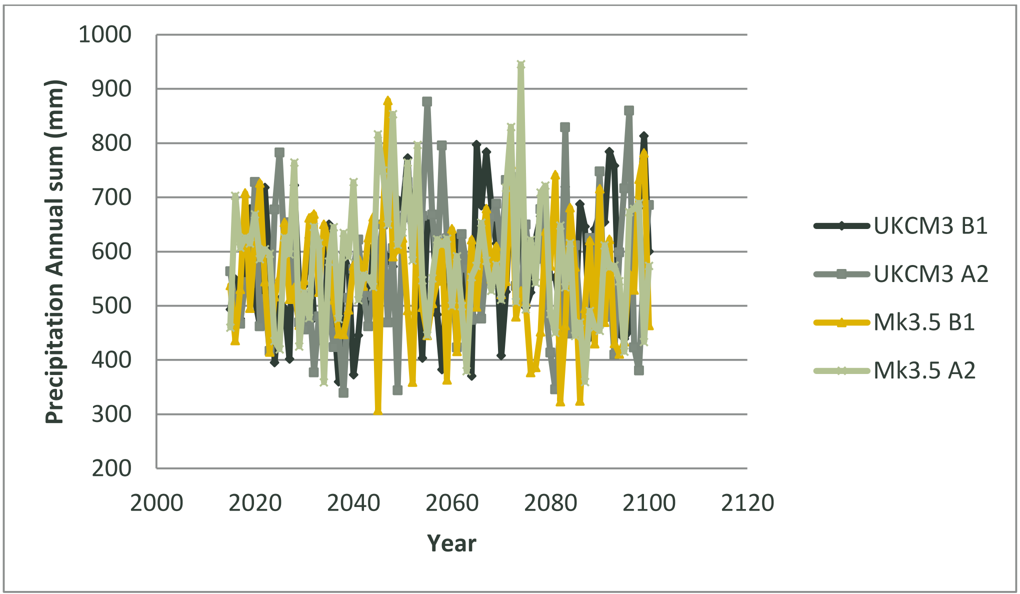


Figure 8. Comparison of the average precipitation for Victoria for the climate projections for UKCM3 B1 (low), UKCM3 A2 (med.-high), Mk3.5 B1 (low) and Mk3.5 A2 (med.-high) over the years 2015-2100

Victoria wide forest growth modelling was undertaken with EVCDF as the EVC type for the carbon farming land use. The carbon sequestration results from this modelling using four future climate projections CSIRO Mk 3.5 B1, CSIRO Mk 3.5 A2, UKCM3 B1 and UKCM3 A2 are shown in Table 7. The DELWP forest growth model was run for the years 2015-2100 and the carbon sequestration rates for the years 2030, 2050, 2070 and 2090 was extracted. The calculations were undertaken on a Victoria-wide basis excluding areas such as Victorian public land, urban land and farming/cropping infrastructure. For most of the climate projections the rate of carbon sequestration is lower in 2070 relative to other years, except for the UKCM3 A2 model which is lowest in 2050. For CSIRO Mk 3.5 with a medium-high A2 emissions scenario, the carbon sequestered is lower for all years, relative to the results using a low emissions scenario B1. However, for the UKCM3 A2 model (medium-high emissions), the carbon sequestered is higher for the years 2070 and 2090, relative to the results for UKCM3 B1 (low emissions). The lowest carbon sequestration rate in 2090 is predicted for UKCM3 B1 while the temperature for this climate projection was lower than the other projections for 2080 to 2090. This could indicate that the lower carbon sequestration rate relative to other climate projections could be related to a lower temperature.

The EVC types EVCWW and EVCMA were used for the carbon farming land use in the DELWP forest growth model and the carbon sequestration results are compared (Table 8). The carbon sequestration results were extracted for the years 2030, 2050, 2070 and 2090. The forest growth model was simulated using the climate projection Mk3.5 A2, as this is a medium-high emissions scenario. Both EVCMA and EVCWW have a high rate of average carbon sequestration in 2050, relative to other years. The maximum carbon

Model and Emm. Scn.	Year	max	mean	std dev
Mk 3.5 B1	2030	48.4	25.3	5.5
Mk 3.5 B1	2050	41.2	23.8	3.5
Mk 3.5 B1	2070	46.0	21.0	5.2
Mk 3.5 B1	2090	49.1	28.0	5.4
Mk 3.5 A2	2030	45.2	22.9	7.0
Mk 3.5 A2	2050	45.0	23.7	4.8
Mk 3.5 A2	2070	44.3	19.4	5.7
Mk 3.5 A2	2090	46.6	26.6	5.2
UKCM3 B1	2030	44.1	24.4	7.7
UKCM3 B1	2050	41.4	22.1	4.9
UKCM3 B1	2070	57.7	21.5	7.8
UKCM3 B1	2090	49.4	24.9	6.1
UKCM3 A2	2030	43.5	23.2	9.5
UKCM3 A2	2050	40.9	20.6	5.9
UKCM3 A2	2070	43.8	22.6	4.6
UKCM3 A2	2090	48.5	26.4	4.9

Table 7. Victoria-wide maximum (max), mean and standard deviation (std dev) results for sequestered carbon with varying climate projections for the years 2030, 2050, 2070 and 2090 in CO_2-e t/ha/yr.

Year	EVCMA max	EVCWW max	EVCMA mean	EVCWW mean
2030	47.4	45.2	19.5	23.1
2050	47.0	45.0	27.8	24.9
2070	41.5	44.0	21.2	18.6
2090	44.3	47.0	21.8	25.3

Table 8. Victoria-wide maximum (max) and mean carbon sequestration predicted for EVCMA and EVCWW simulations for the years 2030, 2050, 2070 and 2090 in CO_2-e t/ha/yr for Mk3.5 A2.

sequestration rate is higher for EVCMA, relative to EVCWW for 2030 and 2050. Lower rainfall occurs for Mk3.5 A2 for the period 2051-2070, relative to other years, and this corresponds to the lowest carbon sequestration rate for EVCWW in 2070. The years 2051-2070 would be most relevant to any change in carbon sequestration growth rate at 2070, relative to other years. We would expect EVCWW to grow more slowly during a low rainfall period, such as this.

Table 9a and 9b present the results of the forest growth model simulations where the model was set to start at current times (2015) and in the future (2050), for future climate projections using EVCDF as the carbon farming land use. A higher rate of carbon sequestered is predicted for the first 15 years and the rate is lower over 40 years, regardless of when the simulation is started. When the model is started at 2050 (i.e. in a warmer climate), carbon sequestered is higher relative to the simulation starting in 2015 for all climate projections for plus fifteen years. The UKCM3 B1 projection is the lowest in temperature for the climate projections and there is actually a higher carbon sequestration rate for 2055 (+40 years) relative to 2090 (+40 years) related to this projection. For all of the other projections, the +40 year carbon sequestration rate is higher for simulations started in 2050 (e.g. 2090), compared to those started in 2015 (e.g. 2055). This could be related to these climate projections having significantly higher temperatures from about 2060 onwards, whereas the UKCM3 B1 projection rises more slowly.

Model	Started 2015	max	mean	std dev
Mk 3.5 B1	2030	48.4	25.3	5.5
Mk 3.5 B1	2055	47.1	21.7	4.0
Mk 3.5 A2	2030	45.2	22.9	7.0
Mk 3.5 A2	2055	43.6	21.5	4.8
UKCM3 B1	2030	44.1	24.4	7.7
UKCM3 B1	2055	45.4	23.4	4.2
UKCM3 A2	2030	43.5	23.2	9.5
UKCM3 A2	2055	41.6	21.9	5.8

Table 9a For simulations starting in 2015, the Victoria-wide maximum (max), mean and standard deviation (std dev) of carbon sequestered for various climate projections in CO_2-e t/ha/yr for EVCDF.

Model	Started 2050	max	mean	std dev
Mk 3.5 B1	2065	49.2	27.5	5.1
Mk 3.5 B1	2090	43.7	25.8	3.5
Mk 3.5 A2	2065	42.3	24.3	5.0
Mk 3.5 A2	2090	42.5	24.7	3.0
UKCM3 B1	2065	44.8	29.8	5.5
UKCM3 B1	2090	42.3	20.4	3.8
UKCM3 A2	2065	47.4	28.0	5.6
UKCM3 A2	2090	41.5	23.5	3.4

Table 9b For simulations starting in 2050, the Victoria-wide maximum (max), mean and standard deviation (std dev) of carbon sequestered for various climate projections in CO_2-e t/ha/yr for EVCDF.

4. Carbon sequestration using the CSIRO and DELWP models

The predicted rates of carbon sequestration for all live biomass (including roots) for the Murray Basin NRM Cluster were modelled across Victoria, NSW and South Australia using the CSIRO 3PG-2 model and for Victoria only using the DELWP 3PG+ model as this currently only has access to Victorian data. The forest growth models were simulated over a 40 year period. Figure 9 details the carbon sequestration rates predicted using the CSIRO 3PG-2 model based on current climate variability. As a comparison, Figure 10 shows the DELWP 3PG+ carbon sequestration prediction rates using EVCMA as the carbon farming land use type under the low emissions scenario Mk3.5 B1, while Figure 11 is the result using EVCWW for the same scenario. The carbon sequestration rate predicted using the CSIRO forest carbon model is approximately 2 times less than the results predicted by the DELWP model.

There were some similarities in the overall spatial patterns for the two forest growth models. For example, the highest levels of carbon sequestration were present in the southern and south-eastern regions, while the north-western areas had the lowest in both the CSIRO 3PG-2 and DELWP 3PG+ (EVCMA for carbon farming land use) models. The average rainfall pattern (1900-2005) for the Murray-Darling Basin is highest in the southern and eastern parts (see figure 12). The areas receiving greater than 600mm approximately correspond to the areas of highest carbon sequestration for both the CSIRO and DELWP models. Rainfall appears to be the main driver for the spatial variation in carbon sequestration. The DELWP model was run with high resolution soil data and there appears to be some relationship between carbon sequestration and soil type. Figure 13 shows the Soil Surface Texture from the Department of Primary Industries (http://vro.depi.vic.gov.au/dpi/vro/vrosite.nsf/pages/soil_texture-upper-subsoil) and there appears to be some correspondence between loam (red) or clay soil (blue/purple/green) and high carbon sequestration. The correspondence between soil moisture, the ability for the soil to retain moisture and carbon sequestration is likely to be important.

Within Victoria, comparison of the EVCMA and EVCWW results indicated that more carbon was stored overall for the simulation using EVCMA. EVCMA could be considered a suitable EVC class for the Mallee CMA and is a slower growing species needing less rainfall, relative to EVCWW. The modelling results for EVCMA show greater carbon sequestration over the Mallee CMA, relative to EVCWW, as expected. Similar rates of carbon sequestration for both EVCWW and EVCMA are found over the alpine regions of the Murray Basin, which receives higher rainfall.

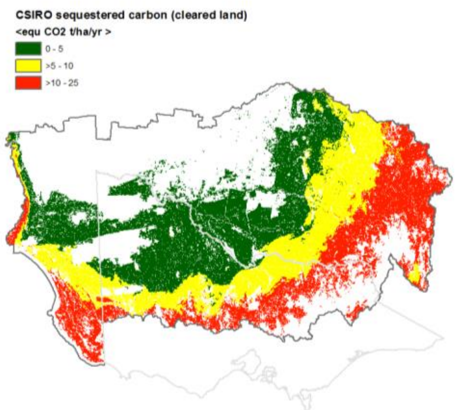


Figure 9. Carbon sequestration predictions using the CSIRO 3PG-2 model for the whole of the Murray Basin NRM Cluster in CO_2-e t/ha/yr based on the current climate.

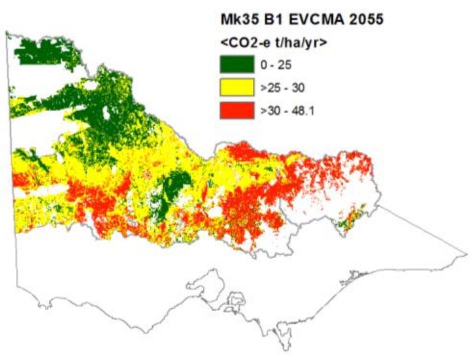


Figure 10. Carbon sequestration predictions using the DELWP 3PG+ model for the Victorian component of the Murray Basin NRM Cluster only in CO_2-e t/ha/yr for the Mk3.5 B1 emissions scenario with EVCMA as the EVC type for the carbon farming land use (2015-2055).

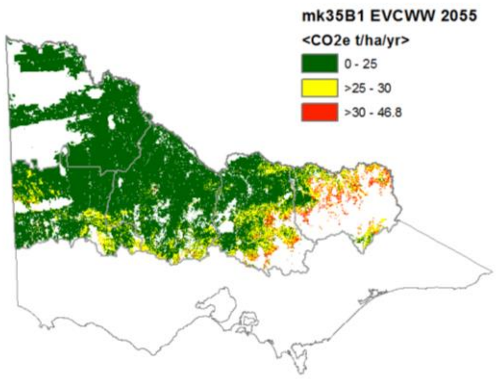


Figure 11. Carbon sequestration predictions using the DELWP 3PG+ model for the Victorian component of the Murray Basin NRM Cluster in CO_2-e t/ha/yr for the Mk3.5 B1 emissions scenario with EVCWW as the EVC type for the carbon farming land use (2015-2055)

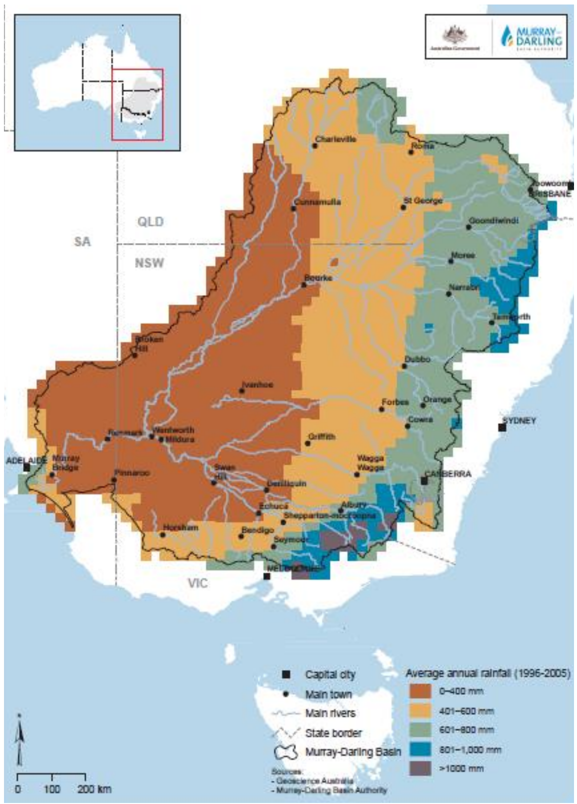


Figure 12. Long-term average annual rainfall(mm), 1900-2005 (taken from the Murray-Darling Basin Authority http://www.mdba.gov.au/sites/default/files/cartographicmapping/156_Rainfall_Coverage_1996_2005.pdf)

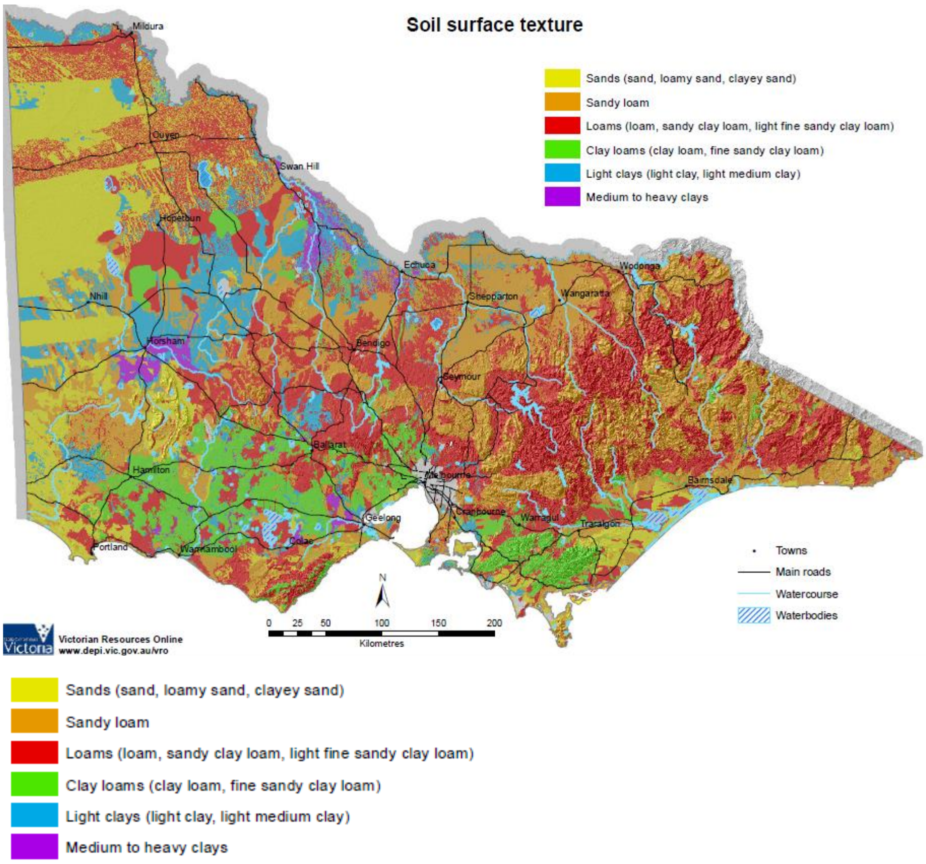


Figure 13. Soil surface texture map for Victoria from Department of the Environment and Primary Industries.

Comparison of the DELWP and CSIRO forest growth models

The rate of carbon sequestration is important for helping to determine the likely economic outcomes of carbon farming. Accurately predicting rates of growth (and hence rates of carbon sequestration) at the farm scale is difficult as there are many variables that control plant growth, many of which we know little about. Consequently, it is important to understand the limitations of this modelling study.

Measured or estimated rates of carbon sequestration for a broad range of mixed Australian native species plantings were used to calibrate the CSIRO 3PG-2 model. The model calibrations are based on plant biomass data grown across a wide range of environmental and growth conditions. Actual plant growth will vary according to the mix of species, soil type and conditions such as previous land use, the amount of stored soil water at time of planting, management such as control of weeds, control of grazing, fertilizer application and planting design. Planting geometry such as block or belts can be important for carbon sequestration as edge effects influence intra-specific competition and can substantially increase the growth of the outer rows of trees. The amount of carbon sequestration is determined by such factors as planting geometry, stocking and species (Paul et al. 2013).

The CSIRO forest growth model is simulated using historical climate as a proxy for future climate, enabling the impacts of natural climate variability on carbon sequestration to be investigated. It is important to accurately simulate climate variability as it determines the survival and growth of plantings and therefore carbon sequestration rates.

In contrast, the DELWP forest growth model is simulated using a range of future climate projections to help predict what may happen to carbon storage under different climate scenarios. Both the climate projections and the response of plantings to elevated carbon dioxide and temperatures are highly uncertain. The response of forest growth to increased levels of carbon dioxide was not included in either model.

Uncertainty in forest growth modelling

Some of the most important uncertainty factors for forest growth modelling and therefore carbon sequestration predictions are:

1. Changes in average climatic conditions. Changes in average annual temperature and rainfall, and increases in the concentration of atmospheric carbon dioxide will all potentially affect growth and hence the amount of carbon sequestered. There are scarce data in Australia to predict the impacts of climate change (increased temperatures and elevated carbon dioxide levels) on native vegetation. In a detailed modelling study, Battaglia et al. (2009) showed that growth of radiata pine in commercial plantations under projected future climates could change in either direction, depending upon how trees responded to increased levels of CO_2. Most plant species respond to elevated CO_2 levels by decreasing their water use (Duursma et al. 2011). Plant life stage may also influence plant growth responses. Lewis et al. (2013) found that faster growing *Eucalyptus* seedlings were more vulnerable under drought conditions, relative to slower growing seedlings. In a different study, *Eucalyptus globulus* trees were found to have limited success in laboratory simulated warmer climatic conditions (Crous et al. 2013).

2. Extreme weather events. Perhaps more important than changes in average conditions will be the impacts of extreme weather events, most notably the possibility of more prolonged, intense droughts and heatwaves with concomitant increases in extreme fire weather conditions. For the year 2020, the Forest Fire Danger index (FFDI) is predicted to increase by up to 4% in the low Conformal Cubic Atmospheric Model (CCAM Mark 2) and up to 10% in the high emission scenarios (CCAM Mark 3). The 2050 simulation for low emissions scenario predicts a possible 8% increase in the FFDI for the low and a 10-30% increase for the high emission scenario (Lucas et al. 2007). The vulnerability and ability of plant species to recover from drought is species-dependent and related to 'threshold conditions' of the duration and intensity of the drought being exceeded (Choat et al. 2012). Forest carbon plantings may be particularly susceptible to extreme heat and drought conditions when young before roots are sufficiently established to access water stored

Advantages	Disadvantages
No harvesting	Establishment costs are high
Can include biodiversity improvements	Can displace grazing/cropping land
Can improve salinity issues	Large areas of land may be required
Can be combined with the production of other forest products	Extended management time required

Table 7. Advantages and disadvantages of carbon farming projects related to economic, social and practical constraints.

deeper in soil horizons. The increased FFDI under future climate change and accompanying higher likelihood of fire is a also a significant risk to consider when undertaking carbon farming projects.

3. Impacts on ecosystem carbon sequestration. Most accounting systems for forest carbon plantings estimate only the amounts of carbon sequestered in live vegetation, including the roots. While it is true that vegetation is the main storage of carbon in forests, soil is also a large and important store of carbon. Soil carbon is, however, also sensitive to changing climatic conditions and influences the net amount of CO_2 taken up from, or emitted to, the atmosphere in any given year. In cool, wet years, uptake of CO_2 from the atmosphere during plant photosynthesis proceeds at a rate greater than that released through plant respiration, decomposition of dead plant material and soil released CO_2. This results in net carbon sequestration from the atmosphere. In hot, dry years typified by drought, limited water availability limits plant growth but not to the same extent as respiration. This can result in a substantial net release of CO_2 to the atmosphere. These results are exemplified in the recent study of Poulter et al. (2014) who showed the sensitivity of carbon stored in semi-arid systems in Australia to prevailing rainfall conditions.

4. Species choice. Given the above it is clear that what is planted in today's climate might not be the species best suited for future climates. Some species or genotypes may be able to adapt to changed climatic conditions to cope with increased temperature or changed rainfall patterns but others may not be able to survive or will grow more slowly or more poorly. Only a small number of studies exist indicating the vulnerability and adaptability of Australia species to changes in climate. In addition, the scale and severity of impacts will depend upon the particular bioclimatic region and the extent of change. For example, it might be expected that species already growing in relatively hot, dry climates may continue to be suited to harsh conditions. In contrast, wetter and cooler areas more impacted by climate change may see a shift in species suitability. Selecting tree species that appear to be more resistant to (e.g. Mallee species) or combinations of species systems that may be more resilient to change (i.e. are able to readily recover following disturbance) should be considered when new on-ground projects are established.

Economic, social and practical constraints to the uptake of carbon farming

There are a range of economic, social and practical constraints on carbon farming projects (Table 10):

- Land for carbon farming will be in competition with grazing/cropping land and therefore food production. The carbon price needs to be high enough to compete with returns on food cropping/grazing production for landowners to adopt carbon planting in favour of their existing farming practices. There are some concerns from the public in relation to the impacts of carbon farming on "food production and water availability" (Mitchell et al., 2012). Water security and higher demand for food with an increasing population are both likely to be important issues in the future.
- Carbon farming projects are different to commercial forestry projects in terms of practical and economic constraints. The carbon payment that the carbon farmer receives can be in the form of an annuity so that there is a regular investment return. The advantage of carbon farming projects is that there is no cost for harvesting and therefore no need to confine plantings close to processing facilities. The establishment costs of carbon plantings are substantial, relative to other farming practices and this could be prohibitive. Environmental Carbon Plantings are more expensive to establish than monocultures and are therefore less profitable. Financial incentives for the selection of environmental plantings rather than monocultures may be required so that these types of plantings are chosen for carbon farming. Theorists have suggested that regulations may need to be implemented to enforce the use of Environmental Carbon Plantings in areas that have a high importance for conservation (Crossman et al., 2011), however, in practice this is unlikely to occur.
- Small carbon farming projects may be more compatible with existing farming practices and carry less financial risk for farmers. At current carbon prices, landowners are more likely to undertake carbon plantings on marginal farm land that has low land value, rather than valuable farming land (Schirmer and Bull, 2011). The gains to be made from carbon sequestration credits are currently quite low for small areas of carbon farming. Other constraints for the adoption of carbon farming are likely to be the "relative advantage" and the "trialability" of the practice (Pannell et al. 2006). The Relative Advantage of a farming practice consists of a range of economic factors such as input costs and profits as well as its compatibility with existing practices. The likelihood of adoption of new practices is more likely for larger properties.

- There may be multiple gains for carbon farming projects including improvements to salinity and additional income streams. Mallee plantings are popular with landowners as they are suited to low rainfall areas (300-600 mm annual) and they have the added advantage of reducing salinity. There are potential additional incomes sources from Mallee plantings, such as Eucalyptus oil and biofuels.

Biodiversity could be improved by the uptake of carbon farming, however this depends on the goals of individual landowners. Studies have shown that the reason for holding the land is an important factor (eg. Agriculture versus lifestyle landholder). The adoption of conservation related carbon farming is related to the landholders' individual beliefs and personal goals.

5. Conclusions

For an overview of issues related to carbon farming in the form of a user-friendly checklist, see Appendix A.

- Carbon farming projects are likely to become more profitable if the carbon price rises, however there is currently uncertainty related to the future carbon market.
- Establishment costs of $1000/ha and a discount rate of 10% would allow profits in the Murray Basin NRM Cluster, given a $20/t CO_2-e carbon price.
- If establishment costs were $3000/ha and the discount rate was 10%, carbon farming profitability would be challenging in the Murray Basin.
- Highest carbon sequestration potential is in the southern and eastern sides of the Murray Basin and the lowest is in the northern and western regions
- The main driver for spatial patterns of carbon sequestration is the average rainfall pattern, with high rainfall corresponding to high carbon sequestration
- A secondary driver for carbon sequestration could be related to soil type and soil moisture
- There is high uncertainty related to climate change projections associated with rainfall patterns as climate models have low skill in predicting rainfall
- DELWP forest growth model results show that carbon sequestration rates could increase in a warmer climate, such as might occur in the year 2050.
- There are risks to carbon farming related to the likely increased frequency of hot extremes and the associated risk of bushfires

6. Potential Knowledge Gaps and Future Research

There are uncertainties as to the effect of drought and bushfire risk on carbon farming projects and under the legislation, farmers are expected to replace damaged trees as part of their carbon farming management agreement. The contract that the landowner enters into indicates that trees damaged due to bushfires, disease and pests must be replenished in terms of their carbon storage.

Supplementary plantings may be used in a carbon farming project rather than a revegetation of cleared land. Landowners often have areas of remnant native vegetation and these areas could be converted to carbon farming zones by adding environmental plantings. This would require an adjustment of forest growth modelling in terms of the estimated carbon sequestration and would warrant further investigation.

The effect of forest regeneration due to fencing areas of land and exclusion of grazing animals would also require a different forest modelling approach. Including the natural succession and seed dispersal of plants would require a forest model with algorithms for such processes. Suitable data would be needed to underpin such models that is relevant to Australian native species.

References and further reading

ALMEIDA, A.C., PAUL, K.I., SIGGINS, A., SANDS, P.J. POLGLAS, P., MARCAR, N.E., JOVANOVIC, T., THEIVEYANATHAN, S., CRAWFORD, D.F.ENGLAND, J.R., FALKINER, R., HAWKINS, C. & WHITE, D. 2007. Development, calibration and validation of the forest growth model 3-PG with an improved water balance. Ensis Client Report, 1786.

BATTAGLIA, M., BRUCE, J., BRACK, C. & BAKER, T. 2009. Climate Change and Australia's plantation estate: Analysis of vulnerability and preliminary investigation of adaptation options. Report for Forest and Wood Products Australia.

CHOAT, B., JANSEN, S., BRODRIBB, T.J., COCHARD, H., DELZON, S., BHASKAR, R., BUCCI, S.J., FIELD, T.S., GLEASON, S.M., HACKE, U.G. JACOBSEN, A.L., LENS, F., MAHERALI, H., MARTINEZ-VILATA, J., MAYR, S., MENCUCCINI, M., MITCHELL, P.J., NARDINI, A., PITTERMANN, J., PRATT, R.B., SPERRY, J.S., SPERRY, J.S., WESTOBY, M., WRIGHT, I.J. & ZANNE, A.E. 2012. Global convergence in the vulnerability of forests to drought. Nature. 491, 752-755.

CROSSMAN, N.D., BRYAN, B.A. & SUMMERS, D.M. 2011. Carbon payments and low-cost conservation. Conservation Biology, 25 (4), 835-845.

CROUS, K.Y., QUENTIN, A.G., LIN, Y.-S., MEDLYN, B.E., WILLIAMS, D.G., BARTON, C.V.M. & ELLSWORTH, D.S. 2013. Photosynthesis of temperate *Eucalyptus globulus* trees outside their native range has limited adjustment to elevated CO_2 and climate warming. Global Change Biology, 19, 3790-3807.

DEPARTMENT OF SUSTAINABILITY AND ENVIRONMENT, THE STATE OF VICTORIA. 2007. Technical Manual: Models of the Catchment Analysis Tool (CAT1D Version 22).

DUURSMA, R.A., BARTON, C.V.M., EAMUS, D., MEDLYN, B.E., ELLSWORTH, D.S., FORSTER, M.A., TISSUE, D.T., LINDER, S. & MCMURTRIE, R.E. 2011. Rooting depth explains [CO_2] x drought interaction in Eucalyptus saligna. Tree Physiology, 31, 922-931.

FEIKEMA, P., MORRIS, J., BEVERLY, C., BAKER, T. & LANE, P. 2010. Description of the 3PG+ forest growth model, Department of Forest and Ecosystem Science, The University of Melbourne.

GALLANT, J.C., & DOWLING, T.I. 2003. A multiresolution index of valley bottom flatness for mapping depositional areas. Water Resources Research, 39, 1347.

GORDON, H., O'FARRELL, S., COLLIER, M., DIX, M., ROTSTAYN, L., KOWALCZYK, E., HIRST, T. & WATTERSON, I. 2010. The CSIRO Mk3.5 Climate Model, CAWCR Technical Report, 21.

JEFFREY, S.J., CARTER, J.O., MOODIE, K.M. & BESWICK, A.R. 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling and Software, 16, 309-330.

JOHNS, T.C., GREGORY, J.M., INGRAM, W.J., JOHNSON, C.E., JONES, A., LOWE, J.A., MITCHELL, J.F.B., ROBERTS, D.L., SEXTON, B.M.H., STEVENSON, D.S., TETT, S.F.B. & WOODAGE, M.J. 2003. Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios, Climate Dynamics, 20, 583-612.

LEWIS, J.D., SMITH, R.A., GHANNOUM, O., LOGAN, B.A., PHILLIPS, N.G. & TISSUE, D.T. 2013. Lewis, J.D., Industrial-age changes in atmospheric [CO_2] and temperature differentially alter responses of faster- and slower-growing Eucalyptus seedlings to short-term drought. Tree Physiology, 33, 475-488.

LIU, D.I. & ZUO, H. 2012. Statistical downscaling of daily climate variables for climate change impact assessment over New South Wales, Australia. Climatic Change, 115, 629-666.

LUCAS, C., HENNESSY, K., MILLS, G. & BATHOLS, J. 2007. Bushfire weather in Southeast Australia: Recent trends and projected climate change impacts. Consultancy report prepared for The Climate Institute of Australia. Bushfire CRC and Australian Bureau of Meteorology.

LANDSBERG, J.J. &WARING, R.H. 1977. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management, 95, 209-228.

McKENZIE, N.J., JACQUIER, D.W., ASHTON, L.J. & CRESSWELL, H.P. 2000. Estimation of Soil Properties Using the Atlas of Australian Soils, CSIRO Land and Water, Canberra ACT, Technical Report 11/00.

MITCHELL, C.D., HARPER, R.J. & KEENAN, R.J. 2012. Current status and future prospects for carbon forestry in Australia. Australian Forestry, 75(3), 200-212.

MORRIS, J.D. 2003. Predicting the environmental interactions of eucalypt plantations using a process-based forest model. In: TURNBALL, J.W. (editor), Eucalypts in Asia Conference Proceedings. China, 7-11 April.

NORTHCOTE, K.H., BECKMANN, G.G., BETTENAY, E., CHURCHWARD, H.M., VAN DIJK, DIMMOCK, G.M., HUBBLE, G.D., ISBELL, R.F., McARTHUR, W.M., MURTHA, G.G., NICOLLS, K.D, PATON, T.R., THOMPSON, C.H., WEBB, A.A. & WRIGHT, M.J. 1968. Atlas of Australian Soils, Sheets 1 to 10. With explanatory data. Melbourne, Australia: CSIRO Aust. and Melbourne University Press.

PANNELL, D.J., MARSHALL, G.R., BARR, N., CURTIS, A., VANCLAY, F. & WILKINSON, R. 2006. Adoption of conservation practices by rural landholders. Australian Journal of Experimental Agriculture, 46(11), 1407-1424.

PAUL, K., ROXBURGH, S., RAISON, J., LARMOUR, J., ENGLAND, J., MURPHY, S., NORRIS, J., RITSON, P., BROOKSBANK, K., HOBBS, T., NEUMANN, C., LEWIS, T., READ, Z., CLIFFORD, D., KMOCH, L., ROONEY, M., FREUDENBERGER, D., JONSON, J., PECK, A., GILES, R., BARTLE, J., McARTHUR, G., WILDY, D., LINSAY, A., PREECE, N., CUNNINGHAM, S., POWE, T., CARTER, J., BENNETT, R., MENDHAM, D., SUDMEYER, R., ROSE, B., BUTLER, D., COHEN,

L., FAIRMAN, T., LAW, R., FINN, B., BRAMMAR, M., MINCHIN, G., VAN OOSTERZEE, P. & LOTHIAN, A. 2013. Improved estimation of biomass accumulation by environmental planting and Mallee plantings using FULLCAM. Report for The Department of the Environment. CSIRO Sustainable Agriculture Flagship, Canberra, Australia.

POLGLASE, P., PAUL, K., HAWKINS, C., SIGGINS, A., TURNER, J., BOOTH, T., CRAWFORD, D., JOVANOVIC, T., HOBBS, T., OPIE, K., ALMEIDA, A., CARTER, J. 2008. Regional opportunities for Agroforestry systems in Australia, RIRDC Publication No. 08/176.

POLGLASE, P.J., REESON, A., HAWKINS, C., PAUL, K., SIGGINS, A., TURNER, J., CRAWFORD, D., JOVANOVIC, T., HOBBS, T., OPIE, K., CARWARDINE, J. & ALMEIDA, A. 2011. Opportunities for carbon forestry in Australia: Economic assessment and constraints to implementation. CSIRO, Canberra.

POLGLASE, P.J., REESON, A., HAWKINS, C.S., PAUL, K.I., SIGGINS, A.W., TURNER, J., CRAWFORD, D.F., JOVANOVIC, T., HOBBS, T.J., OPIE, K., CARWARDINE, J., & ALMEIDA, A. 2013. Potential for forest carbon plantings to offset greenhouse emissions in Australia: economics and constraints to implementation, Climatic Change, 121, 161-175.

POULTER, B., FRANK, D., CIAIS, P., MYNENI, R.B., ANDELA, N., BI, J., BROQUET, G., CANADELL, J.G., CHEVALLIER, F., LIU, Y.Y., RUNNING, S.W., SITCH, S. & VAN DER WERF, G.R. 2014. Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle, Nature, 509, 600-603.

RYAN, P., DOERR, V., DOERR, E., Dunlop, M. & GORRDARD, R. 2016. The NRM Adaptation Planning Framework: six steps to transform NRM planning under global change. CSIRO, Australia and the Australian Resilience Centre, Beechworth.

SCHIRMER, J. & BULL, L. 2011. Planting trees for carbon sequestration: what do landholders think? CRC for Forestry Technical Report, 218.

SMITH, C. 2002. 1:250 000 Statewide soil attribute coverage documentation. Centre for Land Protection Research, Department of Primary Industries, Victoria.

SMITH, I. & CHANDLER, E. 2010. Refining rainfall projections for the Murray Darling Basin of south-east Australia –the effect of sampling model results based on performance. Climatic Change, 102, 377-393.

STOTT, P.A., TETT, S.F.B., JONES, G.S, ALLEN, M.R., MITCHELL, J.F.B. & JENKINS, G.J. 2000. External control of 20th century temperature by natural and anthropogenic forcings. Science, 290, 2133-2137.

TIMBAL, B., ABBS, D., BHEND, J., CHIEW, J.C., EKSTROM, M., KIRONO, D., LENTON, A., LUCAS, C., McINNES, K., MOISE, A., MONSELESAN, D., MPELASOKA, F., WEBB, L. & WHETTON, P. 2015. Climate change in Australia Projections for Australia's Natural Resource Management Regions. In: EKSTROM, M., WHETTON, P., GERBIN, C., GROSE, M., WEBB, L. &

JAMES, R. (editors). Cluster Reports, CSIRO and Bureau of Meteorology.
WATTERSON, I.G. 2012. Understanding and partitioning future climates for Australian regions from CMIP3 using ocean warming indices. Climatic Change, 111, 903-922.

Appendix A Carbon farming planning checklist

Carbon farming planning checklist	
Environmental factors to consider	
Site features	What are the slope and run-off issues to consider?
Rainfall at site	Is the rainfall at the site above/below 600mm and how does this impact the carbon planting options?
Weather extremes	Does the site have a high or low risk for bushfire and flooding?
Climate change at site	What are the climate change projections for the region of interest?
Soil quality at site	Are there salinity issues or soil quality issues at the site?
Weed reduction	Will it be necessary to exclude grazing animals from the site?
Alpine or Rainforest areas	If the site is an alpine or rainforest area it is likely to have more ecological sensitivity to climate change?
Plant species choice	Will plant species be chosen based on drought tolerance or biodiversity?
Planting design	Planting in blocks or belts, shelter for young trees, upper-storey or under-storey plantings?
Water availability	Is there enough access to water to enable young seedlings to be watered regularly?
Biodiversity considerations	Does the site have valuable biodiverse resources that would benefit from supplementary plantings?
Underutilised or marginal land	Could marginal land be used for undertaking a carbon farming project?
Economic factors to consider	
Establishment costs	Environmental versus monoculture plantings
Funding availability	Federal ERF, 20 million trees project, state based funding
Farm income streams	Diversification of farm income or changing of farm practices
Risk to investment	Carbon market volatility, risks from bushfire/drought
Land value	Is the land valuable in terms of cropping/grazing?
Size of land available	Is joining a carbon consortium required in order to access funding?
Project resources related to contracts	What will be the costs of drawing up contracts for a carbon farming project?
Estimates of carbon sequestration	Models such as the Reforestation Modelling tool and the FULLCAM model are available for project scoping and reporting
Multiple outcomes	Can the trees be used to produce products after a number of years such as Eucalyptus oil or biofuels?
Financial	What is the investment required and what are the returns, and over what time scales?
Social factors to consider	
Project manager objectives	What are the environmental objectives of the project managers/investors?
Management of project	How long will the project need to be managed for and is this viable for the project management team?

Other carbon farming projects	Can I learn from others who have tried carbon farming or who are also going through the process of setting up a carbon farm?
Future of farming industry	What is the future outlook of the farming industry/community for current farming practices for the site?

Abbreviations

TERM	DEFINITION
CCAM	Conformal Cubic Atmospheric Model
CFI	Carbon Farming Initiative
CO_2-e	Mass of carbon adjusted to the equivalent mass of carbon dioxide
CSIRO 3PG-2	Commonwealth, Science and Industrial Research Organisation Forest Growth Model 3PG-2
DELWP 3PG+	Department of Environment, Land, Water and Planning Forest Growth Model 3PG+
ERF	Emissions reduction fund
EVC	Ecological Vegetation Classes
HadCM3	Hadley Centre Coupled Model Version 3
IPCC	Intergovernmental Panel on Climate Change
NPV	Net Present Value
PLM25	Public land includes state forests, parks and reserved and unreserved Crown land, including estuarine, coastal and marine areas to the 3 nautical mile limit (5.5 km) from the high watermark. This layer is represented at a scale of 1:25 000 and describes the primary management, land manager and the VEAC recommendations.
RCP	Representative Concentration Pathway
SILO	Scientific Information for Landowners
SRES	Special Report on Emissions Scenarios
UKMO	United Kingdom Meteorological Office

Glossary

TERM	DEFINITION
Afforestation	Afforestation is the establishment of a forest or stand of trees in an area where there was no forest.
Algorithm	A process or set of rules to be followed in calculations or other problem-solving operations, especially by a computer.
Average Stock approach	Commercial forest management has cropping rotations and this affects the overall forest growth. An average stock modelling approach takes this into account when calculating the plant biomass and therefore, the amount of carbon.
Biomass	Biomass is defined as the total mass of living plant organic matter expressed as oven-dry tons or oven dry tons per unit area. Estimates may be restricted to the aboveground portion of the vegetation, or to trees only, or to tree components (such as foliage, wood, etc.).
Biophysical	the branch of biology that applies the methods of physics to the study of biological structures and processes.
Bucket Model	Representing volumes of water in a mathematical model, similar to the idea of a bucket. It can be described as a system which has inputs and outputs of a simulated liquid, based on the size of the volume or bucket.
Calibration	Observed data are used to compare to the modelled process and an adjustment or calibration is made in the model, so that the model more closely approaches the observed data.
Canopy conductance	The water uptake by the tree canopy.
Carbon Farming	Planting trees in order to sequester carbon to help offset greenhouse gas emissions
Carbon Price	A carbon price is a cost applied to carbon pollution to encourage polluters to reduce the amount of greenhouse gas they emit into the atmosphere
Carbon Sequestration	The removal of atmospheric carbon dioxide, either through biological processes (such as photosynthesis in plants), or geological processes (such as storage of carbon dioxide in underground reservoirs).
Carbon Sink	A natural or manmade reservoir that accumulates and stores carbon dioxide for an indefinite period
Climate Change	A change of climate attributed directly or indirectly to human activity that alters the composition of the global atmosphere and is in addition to natural climate variability over comparable time periods.
Climate Projection	A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing scenario used, which in turn is based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised.
Climate Variability	Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).
Discount Rate	Future cash flows are discounted at the discount rate; the higher the discount rate, the lower the present value of the future cash flows. Determining the appropriate discount rate is the key to properly valuing future cash flows, whether they are earnings or obligations.
Environmental Plantings	Carbon farming mixed-species plantings sourced from tube stock or direct seeding that are a mix of trees, shrubs and understorey species that reflect the local native vegetation community.

TERM	DEFINITION
Establishment Cost	Establishment costs include the expenses and asset purchases associated with getting a business started
Mallee Plantings	Carbon farming plantings of an approved Mallee Eucalypt species in regions below 600 mm in annual rainfall
Model grid scale	A mathematical model representing a spatial area will have a grid size or resolution, which is represented computationally. This is usually dependent on computing power.
Net Present Value	The difference between the present value of cash inflows and the present value of cash outflows, as a measure of profitability.
Opportunity Cost	The cost of an alternative that must be forgone in order to pursue a certain action. Put another way, the benefits you could have received by taking an alternative action.
Parameterisation	A mathematical approximation or equation describing a physical process.
Present Value	Present value, also called "discounted value," is the current worth of a future sum of money or stream of cash flow given a specified rate of return. See also Discount Rate.
Recharge	Water added to an aquifer. For instance, rainfall that seeps into the ground.
Reforestation	Reforestation is the reestablishment of forest cover, either naturally (by natural seeding, coppice, or root suckers) or artificially (by direct seeding or planting).
Runoff	Water which is not absorbed by the soil and flows to lower ground, eventually draining into a stream, river, or other body of water.
Rotations	In forestry terms, a rotation is the number of years over which an area of land is forested and then cleared to sell forest products.
Soil Carbon	Soil carbon is the generic name for carbon held within the soil, primarily in association with its organic content.
Time-step	A temporal mathematical model will move forward in time at a particular minimum amount and this time-step, is usually limited by computing power.
Water Balance	In hydrology, a water balance equation can be used to describe the flow of water in and out of a system. A system can be one of several hydrological domains, such as a column of soil or a drainage basin.
Water Security	Water security is defined as the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability.

Contact Details

DELWP

Contact person Michelle Cox
Telephone (03) 9637 8114
Email address

Contact person David Adams
Telephone (03) 9637 9800
Email address

Contact person Gordon Forbes
Telephone (03) 9637 9758
Email address Gordon.forbes@delwp.vic.gov.au

Web address delwp.vic.gov.au

CSIRO

Contact person Linda Broadhurst
Telephone (02) 6246 4988
Email address Linda.Broadhurst@csiro.au

Web address www.csiro.au