Description and implementation of a model for simulating carbon dynamics and land clearing impacts for the Injune case study

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Conceptual model of woodland dynamics

Mature vegetation is cleared/poisoned etc. to stimulate grass growth for cattle grazing. Over time the trees recover, resulting in repeated management to maintain adequate grass cover. Extreme management, such as clearing followed by ploughing of the soil to produce pasture is depicted in the bottom diagram. The question mark indicates less certainty about the recovery of pasture back to woodland.

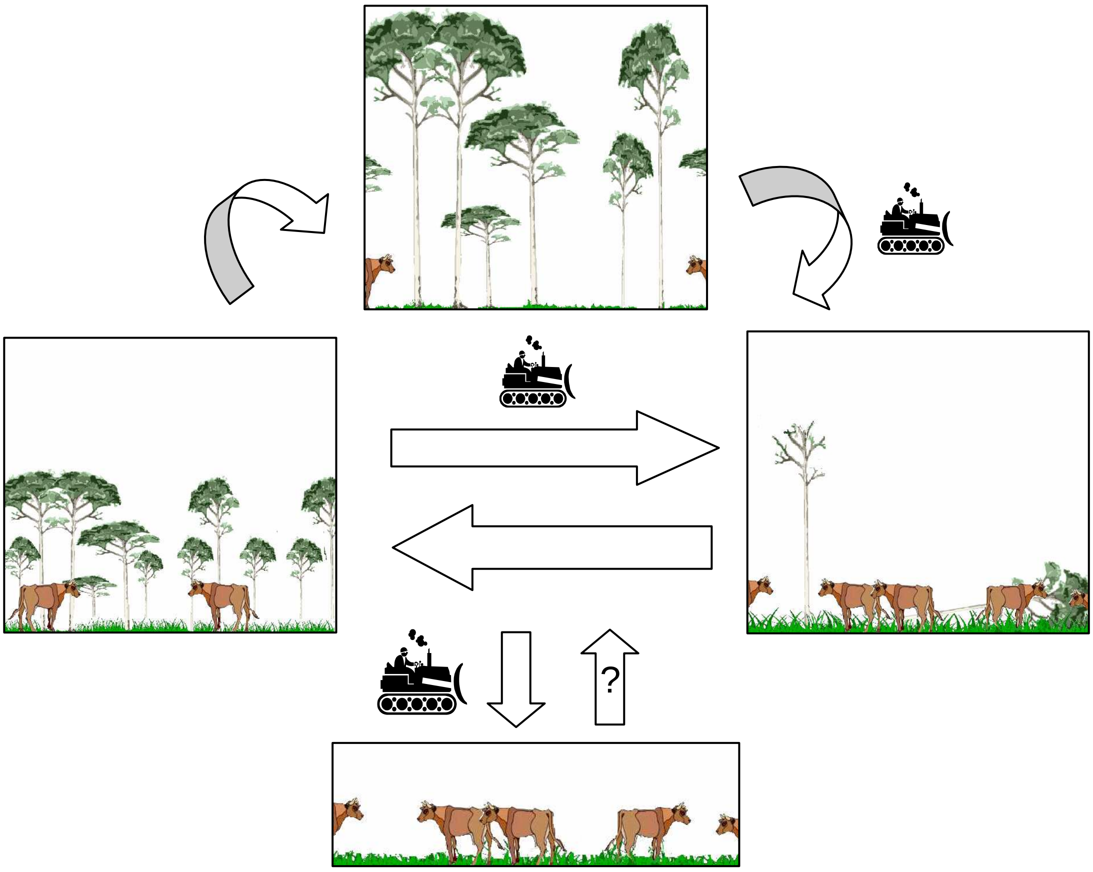


Figure 1. Cartoon of clearing, grazing and grass dynamics.

The vegetation can therefore be split into two main components. Growth of woody vegetation, and growth of the herbaceous grass layer. Clearing activities of various sorts decrease the woody component and promote grass growth. Over time the trees recover and the grass cover declines. Therefore, to maintain stock numbers requires repeated clearing and/or burning, usually in the order of every five-ten years (Ludwig *et al.* 2000).

Representative biomass numbers reflecting the interaction between the grass and tree components are given in Ludwig *et al.* (2000), Burrows *et al*. (1990) and Walker *et al*. (1972, 1986). Burrows *et al*. (1990) describe the interaction between tree-grass competition and climatic variability. In good (high rainfall) years the difference in grass yield between cleared and non-cleared sites is approximately a factor of 2 (1.025 tC/ha on cleared vs. 0.520 tC/ha on uncleared). In poor years the trees compete more strongly with the grasses, resulting in an approximately 4-fold yield difference (0.650tC/ha on cleared vs. 0.130tC/ha on uncleared) .

With respect to carbon dynamics, the grass contributes very little to total carbon stock, but is a significant component of both NPP and litter dynamics, therefore is required for a complete understanding of the system dynamics. One potential model for analysis is given in Figure 2.

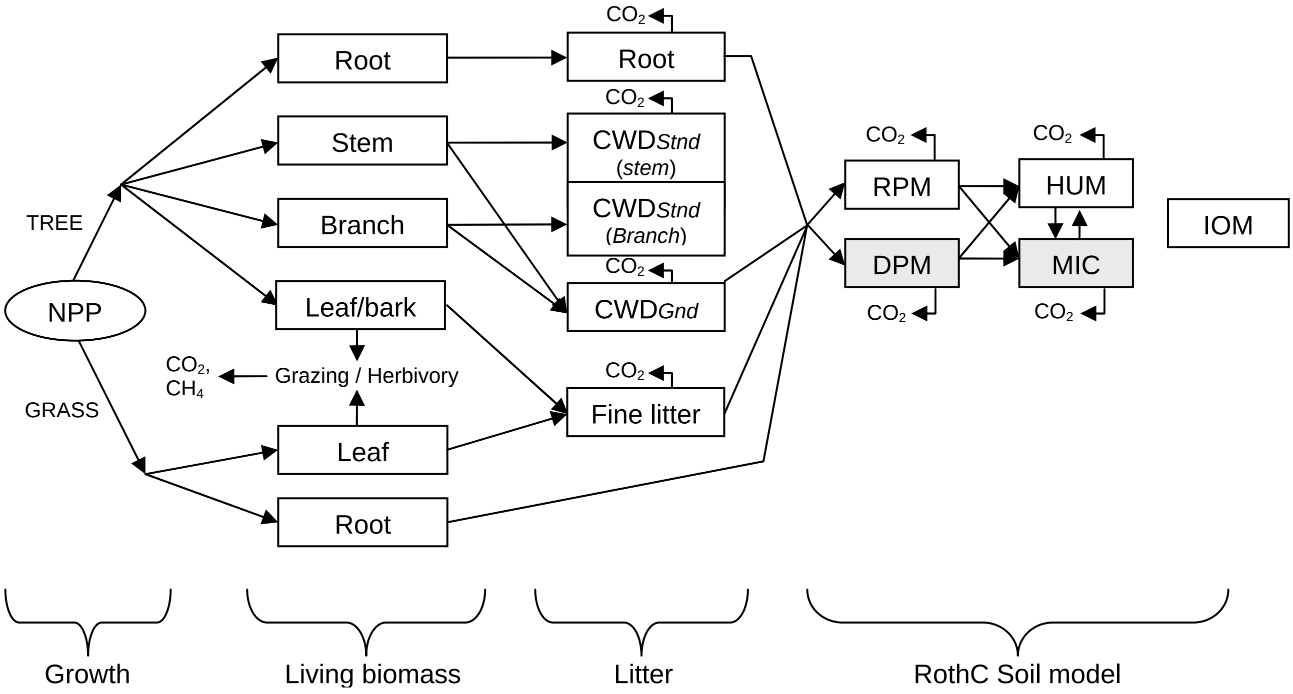


Figure 2. Stock-and-flow diagram of the tree-grass model.

The squares represent stocks of carbon. These are the things we have measurements/estimates for (in addition to some of the fluxes, specifically annual litterfall, annual litter decomposition rates, and annual input of C to the soil pools). The arrows are the fluxes, and are determined by the model parameters (partitioning coefficients, longevities etc.). These parameters need to be estimated. The grayed out boxes in the RothC soil model (DPM, MIC) are very small pools which we don't have estimates for, but are generated internally by the RothC model. The RPM, HUM and IOM pools come from the MIR analysis from Jan Skjemstad's lab. Note that in RothC the IOM is decoupled from the system, as it is assumed to be working on a timescale much longer than the rest of the system.

The different management options (e.g. chaining vs. raking vs. injection poisoning) can be implemented as discrete events which result in instantaneous losses of carbon from the existing pools, movement of carbon among the pools (e.g. stems being converted to CWD), and disruption to fluxes. This formulation also allows us to modify the stocking rates of the cattle (which we have information on), and also potentially look at methane emissions (some of this info is already in Range-ASSESS). This also provides a hook into any economic analyses we might wish to pursue (e.g. running cattle vs. carbon sequestration – if there was a market!)

The challenge is to combine the observations into the above framework for exploring various management scenarios and their various impacts on the terrestrial carbon dynamics. An implementation of the above graphical model is described below, together with some results. The model was initially coded in Excel, but was ported to COINS for main analysis.

Implementing the model

The key climatic driver in these woodland ecosystems is variation in rainfall. Growth was made a simple function of annual precipitation, using the Miami-Oz model (Roxburgh and Davies 2005):

$$NPP_t = \left(460.23 \times e^{-e^{(1.12-0.0014 \times P_t)}} - 460.23 \times e^{-e^{(1.12)}}\right) / a_f$$

Here, NPP_t is the potential *NPP* at time *t* assuming full (mature) vegetation cover. The justification for using a Miami-based approach is the very strong linkage between rainfall and growth in these ecosystems, as reviewed in detail by Le Houerou (1984), and Roxburgh *et al.* (2004).

As noted above, grass growth is dependent upon the tree cover. More trees means less grass growth, and vice versa. There is also an interaction with rainfall. This is implemented by specifying above-ground grass biomass as follows, using a combination of Table 1 in Burrows et al (1990) and Figure 2 of Walker et al (1972).

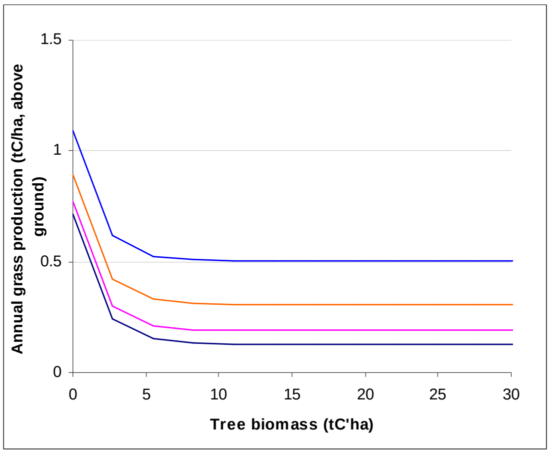


Figure 3. Relationship based on empirical data summarizing the interaction between climate (good and poor rainfall years), above-ground grass growth, and tree cover. The meaning of the different lines is described below. See also Table 2.

The different colours correspond to different rainfall years. The top line (bright blue) is for a high rainfall year (650mm), where annual above-ground grass biomass in cleared plots (AG grass biomass = 1.025 tC/ha; tree biomass = 0 tC/ha) is approximately double that in plots with intact woody vegetation (AG grass biomass = 0.51 tC/ha; tree biomass > 10 tC/ha). The bottom line (dark blue) is for a low rainfall year (425mm), where grass biomass in cleared plots (0.72 tC/ha) is approximately 5 times that in uncleared plots (0.13 tC/ha). These rainfall values correspond to (approximately) the upper and lower 25% quartiles of the long-term precipitation values from the Mitchell climate station. The above-ground grass biomass trends and the rainfall interaction approximately matches the observations reported at the bottom of page 1.

The definitions of 'good' and 'poor' years are user-defined parameters (P_{Good} and P_{Poor}), as is the rate of decay of the function with increasing biomass (set at -0.6 in the above diagram). Mathematically, the curves in the figure are defined as:

$$NPP_t^{G,L} = 0.65 \times e^{-r \times Treebiomass_t} \times \left(\frac{0.65 - 0.13}{0.65} + 0.13 \right) + PU_t$$

Where $NPP_t^{G,L}$ is above-ground grass growth, r is the parameter controlling the steepness of the decline of grass growth with increasing tree biomass, 0.65 is the above-ground forage growth in a poor rainfall year on cleared land (tC/ha/yr), and 0.13 is the same for intact woodland. In the simulations, $r = 0.6$, which makes the advantage of clearing on grass growth last a bit less than 10 years. We assume that grass growth is annual (longevities of carbon in grass leaf and root = 1 year).

The term PU is precipitation use, and is the factor which is responsible for separating the coloured lines in the above graph. It is a simple linear function of rainfall, corresponding to the well known linear relationship between grass growth and rainfall in arid ecosystems (Roxburgh *et al.* 2004; per mm of rainfall, you typically observe 0.001-0.003 tC/ha/yr above-ground grass growth. The function below yields 0.0014 tC above-ground/ha/yr/mm rainfall).

$$PU_t = \left(\frac{0.375}{P_{Good} - P_{Poor}} \right) \times \text{Precipitation} - \left(\frac{0.375 \times P_{Poor}}{P_{Good} - P_{Poor}} \right)$$

Total growth of the grass (above and below ground) is therefore given by

$$NPP_t^{G} = NPP_t^{G,L} \times \left(\frac{1}{a_{G,L}} \right)$$

For each timestep, NPP_t is calculated using the MiamiOZ model (Roxburgh & Davies 2005) as if the vegetation were complete. The fraction of total NPP allocated to grass growth is therefore:

$$a_t^G = \frac{NPP_t^G}{NPP_t}$$

and the fraction into tree growth as

$a_t^T = 1 - a_t^G$, with $NPP_t^T = a_t^T \times NPP_t$

However following tree clearing, the tree growth is reduced in proportion to the biomass removed, and recovers over time in a sigmoidal fashion, as per Klein Goldeweijk *et al.* (1994), and CASS (Roxburgh 2005).

The decline in NPP is controlled by the variable L_t, where in non-disturbance years L_t=1, and when a disturbance occurs, L_t is reduced in proportion to the total above-ground tree biomass lost, and then recovers over time:

$$L_t = \frac{L_{t-1} \times b}{1 + (b-1) \times L_{t-1}}$$

and therefore

$$NPP_t^T = NPP_t^T \times L_t$$

In the implementation of the model, *b* is set to 3. This allows tree production to recover after approx 10 yrs, consistent with growth sponsorship of poplar box from lignotubers.

The dynamics of the carbon are given by the following equations, which are a mathematical translation of Figure 2. The parameter definitions are given in the table which follows the equations:

GRASS CARBON DYNAMICS

$$\frac{dC_{G,L}}{dt} = a_t^G \cdot a_{G,L} \cdot NPP_t - \frac{C_{G,L}}{L_{G,L}} - U_G \cdot C_{G,L}$$

$$\frac{dC_{G,R}}{dt} = a_t^G \cdot a_{G,R} \cdot NPP_t - h \cdot \frac{C_{G,R}}{L_{G,R}} - (1-h) \cdot \frac{C_{G,R}}{L_{G,R}}$$

TREE CARBON DYNAMICS

$$\frac{dC_{T,L}}{dt} = a_t^T \cdot a_{T,L} \cdot NPP_t \cdot L_t - \frac{C_{T,L}}{L_{T,L}} - U_T \cdot C_{T,L}$$

$$\frac{dC_{T,S}}{dt} = a_t^T \cdot a_{T,S} \cdot NPP_t \cdot L_t - (1 - p_{CWDS}) \cdot \frac{C_{T,S}}{L_{T,S}} - p_{CWDS} \cdot \frac{C_{T,S}}{L_{T,S}}$$

$$\frac{dC_{T,B}}{dt} = a_t^T \cdot a_{T,B} \cdot NPP_t \cdot L_t - (1 - p_{CWDS}) \cdot \frac{C_{T,B}}{L_{T,B}} - p_{CWDS} \cdot \frac{C_{T,B}}{L_{T,B}}$$

$$\frac{dC_{T,R}}{dt} = a_t^T \cdot a_{T,R} \cdot NPP_t \cdot L_t - h \cdot \frac{C_{T,R}}{L_{T,R}} - (1-h) \cdot \frac{C_{T,R}}{L_{T,R}}$$

- Tree litterfall in poplar box has been measured as approximately 0.7 tC/ha/yr (see spreadsheet *Poplar box data only.xls*. Therefore:
  $\frac{C_{T,L}}{L_{T,L}} \approx 0.7$ (see also table 3)

LITTER CARBON DYNAMICS

$$\frac{dC_{L,F}}{dt} = \frac{C_{G,L}}{L_{G,L}} + \frac{C_{T,L}}{L_{T,L}} - h\frac{C_{L,F}}{L_{L,F}} - (1-h) \cdot \frac{C_{L,F}}{L_{L,F}}$$

$$\frac{dC_{L,CWDS(S)}}{dt} = P_{CWDS} \cdot \frac{C_{T,S}}{L_{T,S}} - P_{CWDS(S),CWDG} \frac{C_{L,CWDS(S)}}{63.1} - (1 - P_{CWDS(S),CWDG}) \frac{C_{L,CWDS(S)}}{63.1}$$

$$\frac{dC_{L,CWDS(B)}}{dt} = P_{CWDS} \cdot \frac{C_{T,B}}{L_{T,B}} - P_{CWDS(B),CWDG} \cdot \frac{C_{L,CWDS(B)}}{4.1} - (1 - P_{CWDS(B),CWDG}) \cdot \frac{C_{L,CWDS(B)}}{4.1}$$

$$\frac{dC_{L,CWDG}}{dt} = (1 - P_{CWDS}) \cdot \frac{C_{T,B}}{L_{T,B}} + (1 - P_{CWDS}) \cdot \frac{C_{T,S}}{L_{T,S}} + P_{CWDS(S),CWDG} \cdot \frac{C_{L,CWDS(S)}}{63.1} + P_{CWDS(B),CWDG} \cdot \frac{C_{L,CWDS(B)}}{4.1}$$
$$- h \cdot \frac{C_{L,CWDG}}{L_{L,CWDG}} - (1-h) \cdot \frac{C_{L,CWDG}}{L_{L,CWDG}}$$

$$\frac{dC_{L,R}}{dt} = \frac{C_{T,R}}{L_{T,R}} - h \cdot \frac{C_{L,R}}{L_{L,R}} - (1-h) \cdot \frac{C_{L,R}}{L_{L,R}}$$

- Fine litter decomposition was reported by Burrows and Burrows (1992) as having a half life of 2-4 years, therefore $L_{L,F} \approx 3$.
- Decay of standing poplar box trees that had been ringbarked was reported by Burrows *et al.* (2002). Their equation showed rapid loss up to 15-20 yrs, and then a leveling off at about 24% of the original biomass, up to year 64. This is consistent with the rapid drop of the branch component of standing dead trees (half-life 4.1 yrs), and a slower decay of the trunk (half-life 63.2 yrs). See spreadsheet *Poplar box data only.xls*.

SOIL CARBON DYNAMICS

- Soil carbon follows the RothC model.
- Inverse modeling of RothC using our Injune data predicted a required input of organic matter to the soil of 1.26±0.17 tC/ha/y, to match a total organic C content (0-30cm depth) of 53 tC/ha.
- The required organic matter input to the RothC soil model is therefore given by:

$$h \cdot \frac{C_{G,R}}{L_{G,R}} + h \cdot \frac{C_{L,F}}{L_{L,F}} + h \cdot \frac{C_{L,CWDG}}{L_{L,CWDG}} + h \cdot \frac{C_{L,R}}{L_{L,R}} \approx 1.26$$

Disturbance dynamics

Disturbance dynamics, such as fire, chaining, injection poisoning etc. are handled with the following assumptions:

(a) Soil organic matter is not directly disturbed, only indirectly through changes in that rate of organic matter input. This is fine for the disturbances we are concerned with, but not if the soil is cultivated. That would be very easy to add, however, using data in Harms and Dalal (2003) and Skjemstad *et al*. (2004). For example, fire inputs of charcoal to the IOM pool are not considered.
(b) Disturbance effects on the stocks are instantaneous.
(c) Carbon loss can either be direct to the atmosphere, or passed into other carbon pools. The allowed transitions are given below.
(d) NPP is reduced in proportion to the living biomass removed, e.g. if 50% of trees in a patch are removed, total growth of trees declines by 50%. Tree NPP recovers in a sigmoidal fashion as per CASS and Klein Goldeweijk *et al.* (1994).

In the following equations, d_i denotes the proportion of the total pool i that is lost in the disturbance, and $p_{i \to j}$ denotes the proportion of that loss that is passed into pool j. The allowed losses and transitions are:

(i) Grass leaf either goes direct to the atmosphere, or into the fine litter pool

Total loss:

$$C_{G,L} = C_{G,L} \times d_{G,L}$$

Transfer to litter:

$$C_{L,F} = C_{L,F} + p_{G,L \to L,F} \left(C_{G,L} \times d_{G,L} \right)$$

Flux to the atmosphere:

$$= \left(1 - p_{G,L \to L,F} \right) \left(C_{G,L} \times d_{G,L} \right)$$

(ii) Tree leaf either goes direct to the atmosphere, or into the fine litter pool

Total loss:

$$C_{T,L} = C_{T,L} \times d_{T,L}$$

Transfer to litter:

$$C_{L,F} = C_{L,F} + p_{T,L \to L,F} \left(C_{T,L} \times d_{T,L} \right)$$

Flux to the atmosphere:

$$= \left(1 - p_{T,L \to L,F} \right) \left(C_{T,L} \times d_{T,L} \right)$$

(iii) Tree branch either goes direct to the atmosphere, or into the CWD pool, or to standing dead:

Total loss:

$$C_{T,B} = C_{T,B} \times d_{T,B}$$

Transfer to CWD on the ground:

$$C_{L,CWDG} = C_{L,CWDG} + p_{T,B \to L,CWDG} \left(C_{T,B} \times d_{T,B} \right)$$

Transfer to standing CWD:

$$C_{L,CWDS(B)} = C_{L,CWDS(B)} + p_{T,B \to L,CWDS(B)} \left(C_{T,B} \times d_{T,B} \right)$$

Flux to the atmosphere:

$$= \left(1 - p_{T,B \to L,CWDS(B)} + p_{T,B \to L,CWDG} \right) \left(C_{T,B} \times d_{T,B} \right)$$

(iv) Tree stem either goes direct to the atmosphere, or into the CWD pool, or to standing dead:

Total loss:

$$C_{T,S} = C_{T,S} \times d_{T,S}$$

Transfer to CWD on the ground:

$$C_{L,CWDG} = C_{L,CWDG} + p_{T,S \to L,CWDG} \left(C_{T,S} \times d_{T,S} \right)$$

Transfer to standing CWD:

$$C_{L,CWDS(S)} = C_{L,CWDS(S)} + p_{T,S \to L,CWDS(S)} \left(C_{T,S} \times d_{T,S} \right)$$

Flux to the atmosphere:

$$= \left(1 - p_{T,S \to L,CWDS(S)} + p_{T,S \to L,CWDG} \right) \left(C_{T,S} \times d_{T,S} \right)$$

(v) Fine litter and CWD on the ground goes direct to the atmosphere:

Total loss:

$$C_{L,F} = C_{L,F} \times d_{L,F}$$

$$C_{L,CWDG} = C_{L,CWDG} \times d_{L,CWDG}$$

Flux to the atmosphere = total loss.

(v) standing dead trees (either branch or stem component) can either go to the CWD on the ground or go direct to the atmosphere:

Total loss:

$$C_{L,CWDS(B)} = C_{L,CWDS(B)} \times d_{L,CWDS(B)}$$

$$C_{L,CWDS(S)} = C_{L,CWDS(S)} \times d_{L,CWDS(S)}$$

Transfer to CWD on the ground:

$$C_{L,CWDG} = C_{L,CWDG} + p_{L,CWDS(B) \to L,CWDG} \left(C_{L,CWDS(B)} \times d_{L,CWDS(B)} \right)$$

$$C_{L,CWDG} = C_{L,CWDG} + p_{L,CWDS(S) \to L,CWDG} \left(C_{L,CWDS(S)} \times d_{L,CWDS(S)} \right)$$

Flux to the atmosphere:

$$= \left(1 - p_{L,CWDS(B) \to L,CWDG} \right) \left(C_{L,CWDS(B)} \times d_{L,CWDS(B)} \right)$$

$$= \left(1 - p_{L,CWDS(S) \to L,CWDG} \right) \left(C_{L,CWDS(S)} \times d_{L,CWDS(S)} \right)$$

Table 1. Model Parameters

Parameter	Descriptions	Units	Value (‘Fitted’ indicated values were estimated by the calibration procedure. see Table 3)
a_f	Expansion factor for Miami-OZ NPP model	-	Fitted
NPP_t	Net Primary Productivity at time *t*	tC/ha/yr	(a direct function of *af*)
P_{Good}	Good rainfall-year limit	mm	> 650
P_{Poor}	Poor rainfall-year limit	mm	< 425
r	Parameter controlling rate of decline of grass growth with increasing tree biomass	-	-0.6
b	Rate of recovery of tree NPP following	-	3

	disturbance		
$a_{G,poor}$	Annual grass growth at steady state in a poor rainfall year.	tC/ha/yr	0.13
a_t^G	Proportion of total NPP partitioned to grass growth at Time *t*. This is a function of current tree biomass, as described above.	-	-
a_t^T	Proportion of total NPP partitioned to tree growth at Time *t*.	-	$1- a_t^G$
$a_{G,L}$	Partitioning of grass NPP to grass leaves	-	0.5
$a_{G,R}$	Partitioning of grass NPP to grass roots ($1-a_{G,L}$)	-	0.5
$a_{T,L}$	Partitioning of tree NPP to tree leaf	-	Fitted
$a_{T,S}$	Partitioning of tree NPP to tree stem	-	Fitted
$a_{T,B}$	Partitioning of tree NPP to tree branch	-	Fitted
$a_{T,R}$	Partitioning of tree NPP to tree root	-	$1-(a_{T,R} + a_{T,R} + a_{T,R} + a_{T,R})$
U_G	Cattle utilization rate of grass (leaf mass eaten/leaf mass produced)	-	0.0 (i.e. no grazing. Typical values are around 0.3 (Hill *et al.* 2005)
U_T	Cattle utilization rate of trees (leaf mass eaten/leaf mass produced)	-	0.0
$L_{L,L}$	Lifetime of carbon in the grass leaf pool	Years	1
$L_{L,R}$	Lifetime of carbon in the grass leaf pool	Years	1
$L_{T,L}$	Lifetime of carbon in the tree leaf pool	Years	Fitted
$L_{T,B}$	Lifetime of carbon in the tree branch pool	Years	Fitted
$L_{T,S}$	Lifetime of carbon in the tree stem pool	Years	Fitted
$L_{T,R}$	Lifetime of carbon in the tree root pool	Years	Fitted
$L_{I,R}$	Lifetime of carbon in the root litter pool	Years	Fitted
$L_{L,CWDS(B)}$	Lifetime of branch carbon in the standing dead tree pool	Years	4.1 (derived from data in Burrows *et al.* (2002)
$L_{L,CWDS(S)}$	Lifetime of stem carbon in the standing dead tree pool	Years	63.1 (derived from data in Burrows *et al.* (2002)
$L_{L,CWDG}$	Lifetime of carbon in the CWD ground pool	Years	Fitted
$L_{L,F}$	Lifetime of carbon in the fine litter pool	Years	Fitted
P_{CWDS}	Of the living stems and branches that die, the proportion that remain standing	-	Fitted
$P_{CWDS(S),CWDG}$	Of the standing dead stem that is lost, the proportion that falls as CWD	-	0.5
$P_{CWDS(B),CWDG}$	Of the standing dead branch that is lost, the proportion that falls as CWD	-	0.5
h	Humification fraction controlling the amount of organic matter that is input to the RothC soil component of the model	-	Fitted
Clay	RothC required soil clay content	-	40.99%

IOM	Roth C required IOM content	tC/ha	9.99

Table 2. Model state variables (tC/ha)

$C_{G,L}$	Carbon stock in grass leaf pool
$C_{G,R}$	Carbon stock in grass root pool
$C_{T,L}$	Carbon stock in tree leaf pool
$C_{T,B}$	Carbon stock in tree branch pool
$C_{T,S}$	Carbon stock in tree stem pool
$C_{T,R}$	Carbon stock in tree root pool
$C_{L,CWDS(B)}$	Carbon stock in standing dead trees (branch)
$C_{L,CWDS(S)}$	Carbon stock in standing dead trees (stem)
$C_{L,CWDG}$	Carbon stock in CWD
$C_{L,F}$	Carbon stock in fine litter
$C_{L,R}$	Carbon stock in root litter
$C_{S,RPM}$	Carbon stock in soil RPM pool
$C_{S,HUM}$	Carbon stock in soil HUM pool
$C_{S,IOM}$	Carbon stock in soil IOM pool
$C_{S,BIO}$	Carbon stock in soil BIO pool
$C_{S,DPM}$	Carbon stock in soil DPM pool

Climate data

The required climate data was extracted from the BOM database of historical monthly records, for the period 1900-2000, from the Mitchell climate station (Monthly pan evaporation, mean min and max daily temperature and precipitation). Pan evaporation data are available only for the last approximately 30years, and were back-filled using the observed relationship (over that period) between mean daily monthly max temperature and mean daily monthly pan evaporation.

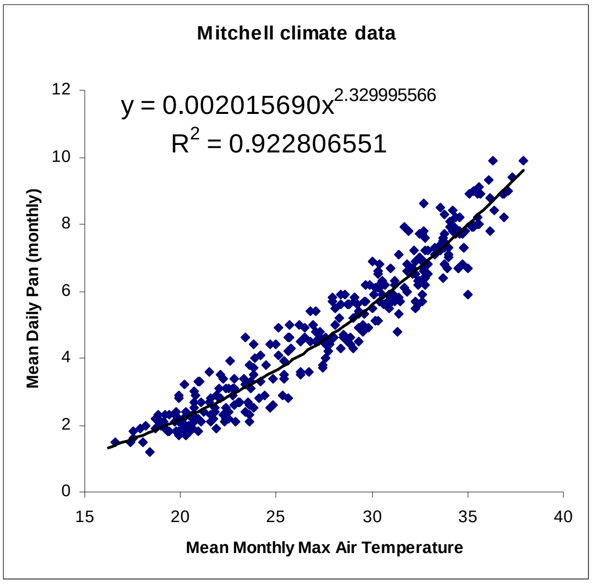


Figure 4. Equation for estimating pan evaporation from mean monthly maximum daily temperatures.

Model calibration

The model was calibrated by function minimization using a combination of genetic algorithm (Michalewicz 1992) and downhill simplex (Press *et al.* 1986). The overall procedure is to specify the observations of stocks and other quantities that are the model outputs against are to be matched against, and then vary the unknown parameters, under constraints, until the model predicts the observations. This is then repeated 1000 times, generating 1000 sets of model parameters that are each equally good predictors of the observations. The observations are drawn from appropriate distributions, based on field sampling. They are:

Table 3. Observations of carbon stocks and fluxes used in the model calibration process.

Observation	**Value (tC/ha or tC/ha/yr)**	**Comments**	**Flux or pool**
Grass leaf stock (long-term average) & Grass root stock	0.385	Constant, as grass dynamics are hard-wired into the code. The value 0.385 is the long-term average above-ground grass mass given the dynamics summarized in Figure 3. Root mass is assumed to be the same as shoot mass (but is probably less).	Pool
Tree leaf stock	1.86±0.99 (normal)	From Injune field survey (n=6). Compares favourable with Burrows *et al.* (2000) data (1.30)	Pool
Tree branch stock	15.85±1.84 (normal)	From Injune field survey (n=6). Compares favourable with Burrows *et al.* (2000) data (14.85)	Pool
Tree stem stock	16.92±3.48 (normal)	From Injune field survey (n=6). Compares favourable with Burrows *et al.* (2000) data (17.85)	Pool
Tree root stock	10.06±1.58 (normal)	From Burrows *et al.* (2000) table 4. Lignotuber and fine root down to 1m.	Pool
CWD (ground)	6.23±2.86 (normal)	From Injune field survey (n=4). Includes two additional sites studied by Woldendorp *et al.* (2002).	Pool
CWD (standing)	0.89-2.0 (uniform)	The range based on two sampling sites within the Injune study area described in Woldendorp *et al.* (2002).	Pool
Fine litter	3.20±0.27 (normal)	Based on n=3 sites from our sampling	Pool
Root litter	2.0-4.0 (uniform)	Unknown – guesstimate	Pool
Rate of litterfall	0.70±0.19 (normal)	Based on n=6 published litterfall estimates, see poplar box data worksheet (Burrows & Burrows 1992; Walker 1981; Grigg and Mulligan 1999)	Flux
Rate of C input to soil	1.26±0.17 (normal)	Based on RothC modeling of soil carbon stocks (Roxburgh *et al.* 2005)	Flux
Constraints on the rate of recovery following disturbance. Assumes 97% loss of tree cover, and subsequent sigmoidal recovery rate of *r*=3			Flux
Years since disturbance	28-33 (uniform)	Based on Lucy's satellite imagery analysis	
Tree biomass (leaf + stem + branch)	69.17-77.78% recovery	The range of biomass across two sites that had been disturbed 28-33	

	(uniform) Corresponds to an observed biomass range of 24.69-27.76tC/ha, and median Poplar Box AG biomass of 35.69tC/ha	yrs previously.	

The above measurements are from minimally disturbed sites (apart from the rate-of-recovery observation), therefore for model calibration we assume steady-state dynamics (although estimates of biomass after disturbance required numerical integration of the equations). The steady state equations use long-term average productivity (*NPP**), and from that, the calculated equilibrium estimate of partitioning of that production to grass (a^{G*}). The steady state equations are given in full below, but can be algebraically simplified further:

$$C_{G,L}^{*} = a^{G*} \cdot a_{G,L} \cdot NPP^{*} \cdot L_{G,L}$$

$$C_{G,R}^{*} = \frac{a^{G*} \cdot a_{G,R} \cdot NPP^{*}}{\dfrac{h}{L_{G,R}} + \dfrac{(1-h)}{L_{G,R}}}$$

$$C_{T,L}^{*} = a^{T*} \cdot a_{T,L} \cdot NPP^{*} \cdot L_{T,L}$$

$$C_{T,S}^{*} = \cdot \frac{a^{T*} \cdot a_{T,S} \cdot NPP_{t}}{\dfrac{(1-p_{CWDS})}{L_{T,S}} + \dfrac{p_{CWDS}}{L_{T,S}}}$$

$$C_{T,B}^{*} = \cdot \frac{a^{T*} \cdot a_{T,B} \cdot NPP_{t}}{\dfrac{(1-p_{CWDS})}{L_{T,B}} + \dfrac{p_{CWDS}}{L_{T,B}}}$$

$$C_{T,R}^{*} = a^{T*} \cdot a_{T,R} \cdot NPP^{*} \cdot L_{T,R}$$

$$C_{L,F}^{*} = \frac{\left(\dfrac{C_{G,L}}{L_{G,L}} + \dfrac{C_{T,L}}{L_{T,L}}\right)}{\dfrac{h}{L_{L,F}} + \dfrac{(1-h)}{L_{L,F}}}$$

$$C_{L,R}^{*} = \frac{\dfrac{C_{T,R}}{L_{T,R}}}{\dfrac{h}{L_{L,R}} + \dfrac{(1-h)}{L_{L,R}}}$$

$$C_{L,CWDS(S)}^{*} = \frac{P_{CWDS} \cdot \dfrac{C_{T,S}}{L_{T,S}}}{\dfrac{P_{CWDS(S),CWDG}}{63.1} + \dfrac{(1-P_{CWDS(S),CWDG})}{63.1}}$$

$$C_{L,CWDS(B)}^{*} = \frac{P_{CWDS} \cdot \dfrac{C_{T,B}}{L_{T,B}}}{\dfrac{P_{CWDS(B),CWDG}}{4.1} + \dfrac{(1-P_{CWDS(B),CWDG})}{4.1}}$$

$$C_{L,CWDG}^{*} = \frac{(1-P_{CWDS}) \cdot \dfrac{C_{T,B}}{L_{T,B}} + (1-P_{CWDS}) \cdot \dfrac{C_{T,S}}{L_{T,S}} + P_{CWDS(S),CWDG} \cdot \dfrac{C_{L,CWDS(S)}}{63.1} + P_{CWDS(B),CWDG} \cdot \dfrac{C_{L,CWDS(B)}}{4.1}}{\dfrac{h}{L_{L,CWDG}} - \dfrac{(1-h)}{L_{L,CWDG}}}$$

To calibrate the model, most parameters were allowed to vary quite freely and without too much constraint – i.e. it is a case of letting the data tell us what the most appropriate sets of parameters are.

This works well, as the litterfall, soil C and dynamic observations place some fairly tight constraints on the range of possible parameters that are allowed.

Thirteen parameters were fitted, based on comparing 13 predicted model quantities with observations (the fact that both are 13 is a coincidence). To fit the parameters, first, 'pseudo-observed' stocks were selected from Table 3 (excluding the data on grass growth under fluctuating environmental conditions). Parameters were selected by the algorithm to yield model prediction that matched those observations. The minimised function was:

$$\Phi = \sqrt{\sum_{i=1}^{13}\left(\frac{C_{i,pred}}{C_{i,obs}}-1\right)^2} \Bigg/ 13$$

i = [$C^*_{G,L}$, $C^*_{G,R}$, $C^*_{T,L}$, $C^*_{T,B}$, $C^*_{T,S}$, $C^*_{T,R}$, $C^*_{L,F}$, $C^*_{L,R}$, $C^*_{L,CWDS}$, $C^*_{L,CWDG}$, litterfall rate, rate of C input to soil, above-ground tree stock after 28-33 years recovery].

where $C_{i, pred}$ is the model-predicted size of carbon pool or flux i, and $C_{i, obs}$ is the 'pseudo-observed' carbon pool or flux size size. Function ϕ can be thought of as the average deviation of all observed carbon pools or fluxes relative to their modeled predictions. The minimization process was halted when the function value fell below 10e-12.

The parameters fitted, their constraints used in the calibration, and the estimated values are given in Table 4.

Table 4. The 13 fitted parameters, and the estimated values based on 1000 model optimisations.

Parameter	Symbol	Constraints	Parameter estimate from calibration. Mean and SD, n=1000)	Comments
MiamiOZ scalar, that gives a range of possible NPP values. Given the rainfall at Injune, the constraints correspond to a potential NPP range of 1.9-9.62.	a_f	0.1-0.5	0.28±0.04	Corresponds to an NPP of 3.47±0.45 tC/ha/yr. This compares favourably with other estimates. (Roxburgh *et al.* 2004 review; average *NPP* = 4.05±1.06sd).
NPP partitioning to tree leaf	$a_{T,L}$	0.1-0.5	0.26±0.06	
NPP partitioning to tree branch	$a_{T,B}$	0.1-0.5	0.35±0.12	
NPP partitioning to tree stem	$a_{T,S}$ $a_{T,R} = 1- (a_{T,S} + a_{,T,L})$	0.1-0.5	0.29±0.12	Therefore, root partitioning is 0.10±0.06
Proportion of living trees that become	P_{CWDS}	0-0.2	0.03±0.01	

stags				
Tree leaf longevity	$L_{T,L}$	0.5-10	3.21±1.71	
Tree branch longevity	$L_{T,B}$	5-50	19.71±8.79	
Tree stem longevity	$L_{T,S}$	5-100	25.62±9.47	
Tree root longevity	$L_{T,R}$	5-100	51.62±29.59	
Fine litter longevity	$L_{L,F}$	1-10	3.27±0.57	Fits with observed decomposition rates of 2-4 (Lee & Corell 1978; Pressland (1982)
Tree root litter longevity	$L_{L,R}$	5-100	15.42±9.73	
CWD on the ground longevity	$L_{L,CWDG}$	1-30	4.02±1.78	
Humification fraction	h	0.001-0.8	0.37±0.07	

Land-clearing simulations

Following calibration, the model was then ready to run in 'forward' mode, where changes in the carbon stocks and fluxes could be simulated trough time. The model equations were integrated using the algorithm ODEINT given by Press *et al.* (1986). A number of scenarios were explored.

Full tree removal

An extreme situation where all above-ground tree biomass is immediately lost to the atmosphere:

```
D_GrassLeaf:=0.00;
DP_GrassLeaf_to_FineLitter:=0.00;
D_TreeLeaf :=1.00;
DP_TreeLeaf_to_FineLitter :=0.0;
D_TreeBranch :=1.00;
DP_TreeBranch_to_CWDGround :=0.00;
DP_TreeBranch_to_CWDStandingBranch :=0.00;
D_TreeStem :=1.00;
DP_TreeStem_to_CWDGround :=0.00;
DP_TreeStem_to_CWDStandingStem :=0.00;
D_FineLitter:=0.00;
D_CWDGround :=0.00;
D_CWDStandingBranch :=0.00;
DP_CWDStandingBranch_to_CWDGround :=0.00;
D_CWDStandingStem :=0.00;
DP_CWDStandingStem_to_CWDGround :=0.00;
```

Herbicide injection

Here 97% of the tree leaf, stem and branch above-ground pools are lost. The branch and stem pools are converted to the standing dead CWD pool. The tree leaves go to fine litter. No recovery of the tree vegetation is allowed in the runs below. Actual successful recovery of the woody vegetation would depend upon available seed sources, good weather conditions for germination and establishment, etc. All too hard to do, so I sidestepped the issue and kept it simple.

```
SuccessionRate:=1.00;
D_GrassLeaf:=0.00;
DP_GrassLeaf_to_FineLitter:=0.00;
D_TreeLeaf :=0.97;
DP_TreeLeaf_to_FineLitter :=1.00;
D_TreeBranch :=0.97;
DP_TreeBranch_to_CWDGround :=0.00;
DP_TreeBranch_to_CWDStandingBranch :=1.0;
D_TreeStem :=0.97;
DP_TreeStem_to_CWDGround :=0.00;
DP_TreeStem_to_CWDStandingStem :=1.0;
D_FineLitter:=0.00;
D_CWDGround :=0.00;
D_CWDStandingBranch :=0.00;
DP_CWDStandingBranch_to_CWDGround :=0.00;
D_CWDStandingStem :=0.00;
DP_CWDStandingStem_to_CWDGround :=0.00;
```

Chaining

97% of above-ground tree biomass is killed, with tree branch and stem pools passed to the CWD ground pool, and tree leaf to the fine litter pool.

```
SuccessionRate:=3;
D_GrassLeaf:=0.00;
DP_GrassLeaf_to_FineLitter:=0;
D_TreeLeaf :=0.97;
DP_TreeLeaf_to_FineLitter :=1.0;
D_TreeBranch :=0.97;
DP_TreeBranch_to_CWDGround :=1.0;
DP_TreeBranch_to_CWDStandingBranch :=0.00;
D_TreeStem :=0.97;
DP_TreeStem_to_CWDGround :=1.0;
DP_TreeStem_to_CWDStandingStem :=0.00;
D_FineLitter:=0.00;
D_CWDGround :=0.00;
D_CWDStandingBranch :=0.97;
DP_CWDStandingBranch_to_CWDGround :=1.0;
D_CWDStandingStem :=0.97;
DP_CWDStandingStem_to_CWDGround :=1.0;
```

Chaining plus fire

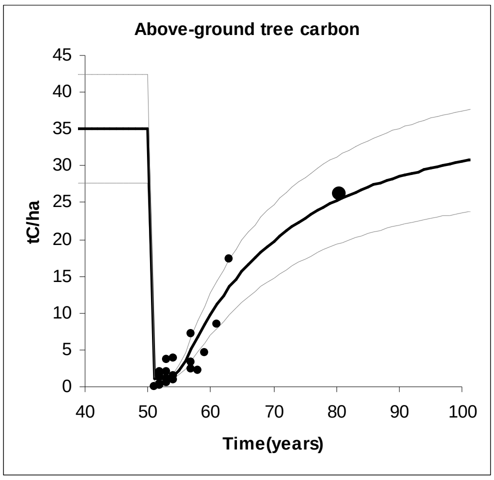
Similar to above, with 97% of existing AG tree biomass lost, but with direct instantaneous loss to the atmosphere from burning as well. It says that when trees are chained, 40% of the leaf is lost back to the atmosphere, and 60% remains on the ground. For branches and stems, 90% (of that 97%) is burnt, and 10% remains as CWD. Also, 90% of the original CWD on the ground is also burnt.

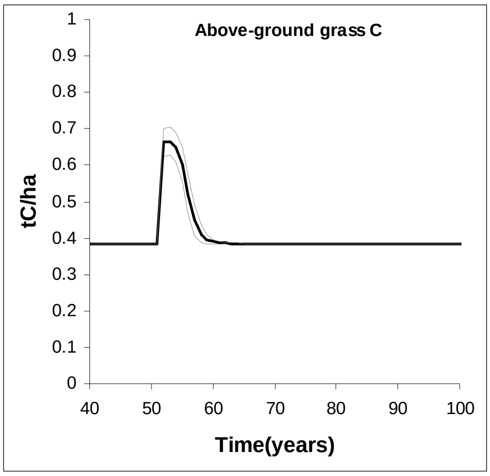
```
SuccessionRate:=3;
D_GrassLeaf:=0.00;
DP_GrassLeaf_to_FineLitter:=0;
D_TreeLeaf :=0.97;
DP_TreeLeaf_to_FineLitter :=0.60;
D_TreeBranch :=0.97;
DP_TreeBranch_to_CWDGround :=0.10;
DP_TreeBranch_to_CWDStandingBranch :=0.00;
D_TreeStem :=0.97;
DP_TreeStem_to_CWDGround :=0.10;
DP_TreeStem_to_CWDStandingStem :=0.00;
D_FineLitter:=0.60;
D_CWDGround :=0.60;
D_CWDStandingBranch :=0.97;
DP_CWDStandingBranch_to_CWDGround :=0.10;
D_CWDStandingStem :=0.97;
DP_CWDStandingStem_to_CWDGround :=0.10;
```

Model Results

In all cases the light gray lines are 95% intervals (SD x 1.96), based on the mean of 1000 model runs, using the 1000 sets of parameters from the genetic algorithm calibration process. For the fluctuating environmental conditions, historical climate data (1900-2000) from the Mitchell climate station was used (annual rainfall for NPP, monthly data for the RothC climate inputs). This data was top-and-tailed to give a total simulation length of 200 years.

(a) Constant (average) environment with single clearing event:

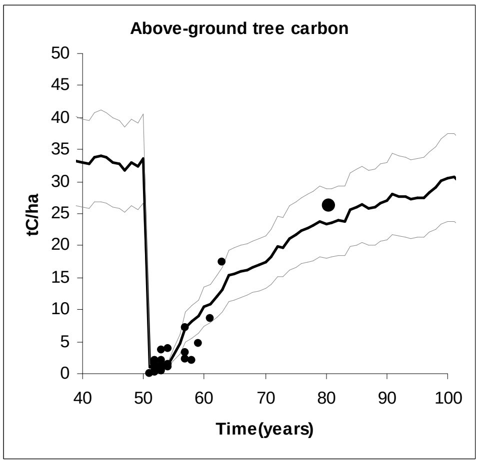


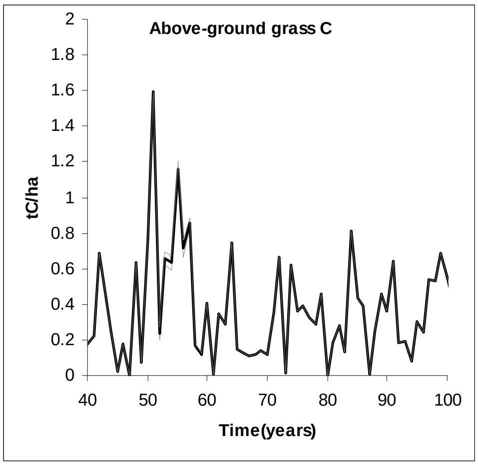


For above-ground tree carbon, the large round dot represent the observed carbon stock 28-33 years after the clearing event, and was used as a constraint in the model calibration (so the mean curve is expected to pass near that point). The smaller round dots are independent data supplied by Steven Bray from the TRAPS database, and also some data from the Injune field sampling. These data can thus be considered validation of the growth-recovery curve of poplar-box woodlands following clearing.

In response to clearing, the grass mass approximately doubles, but declines after about 10 years as the trees recover.

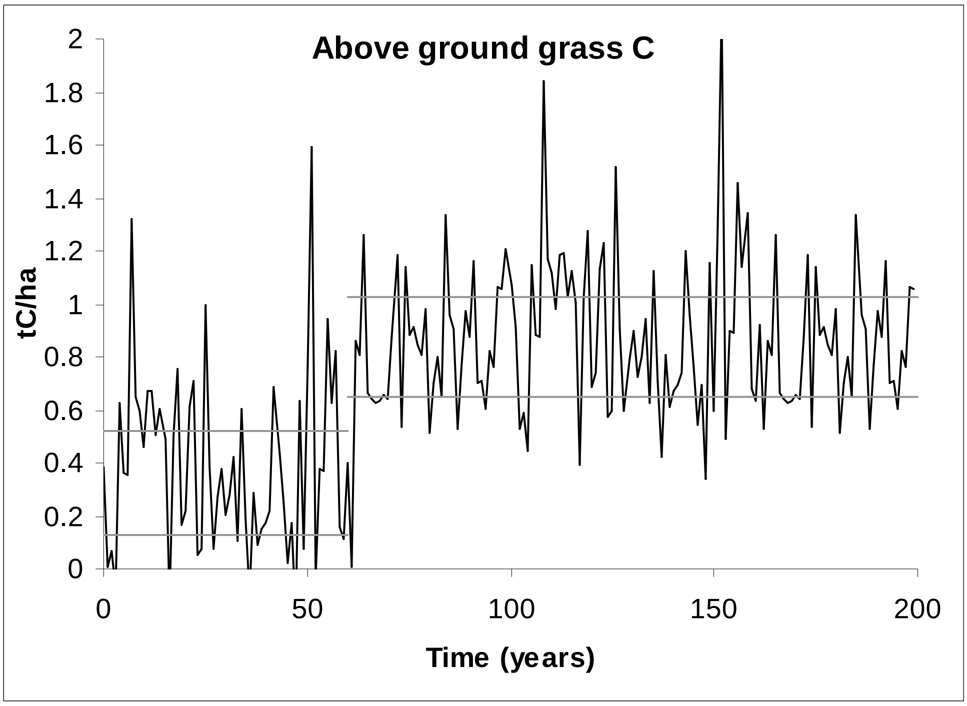
(b) Fluctuating environment with single clearing event:





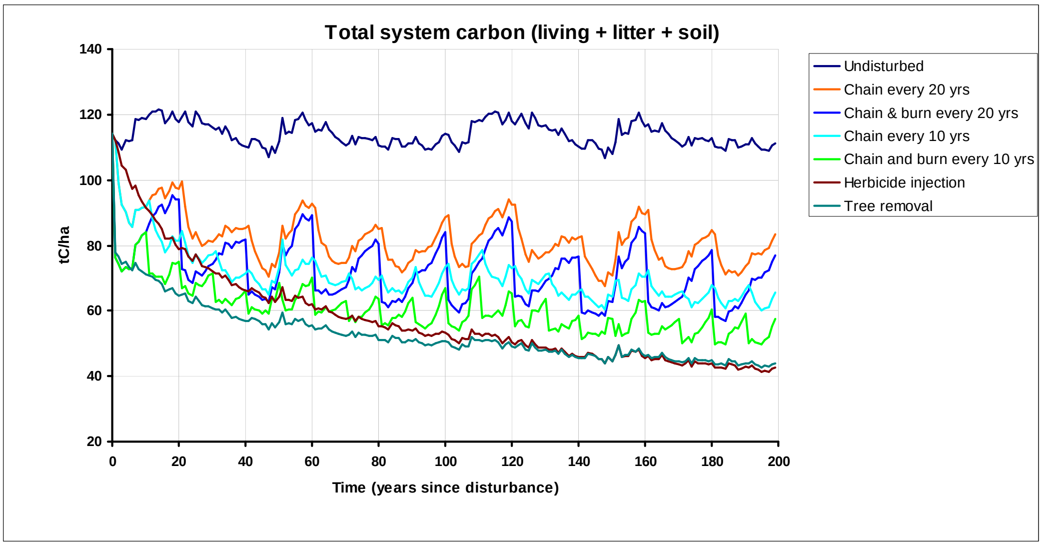
The case above is the same as in the first example, but with fluctuating environmental conditions. This shows that year-to-year fluctuations in natural grass growth are about the same as the grass response to clearing, illustrating the difficulty of land management for grazing in these environments.

(c) Fluctuating environment, grass dynamics following complete tree removal:



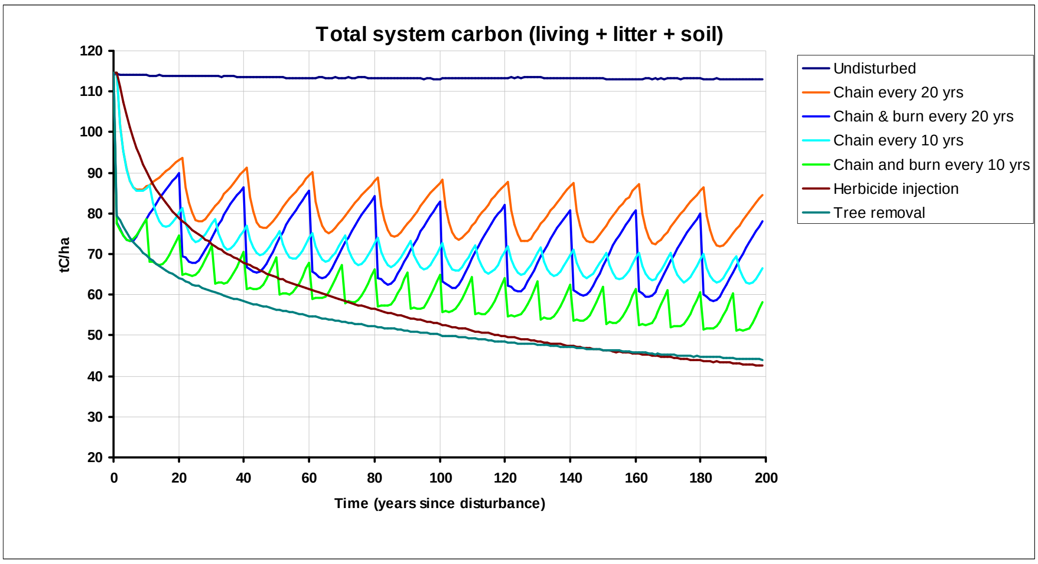
Here, all above-ground trees biomass was removed at year 60, hence the change in above-ground grass carbon represents dynamics of intact and cleared woodland. In intact woodland the grass biomass fluctuates between approximately 0.1 and 0.5 tC/ha, corresponding to poor and good rainfall years respectively. Following clearing the respective fluctuations are 0.6 to 1.2 tC/ha. As mentioned above, these dynamics were tuned to match the observed patterns of grass dynamic following clearing.

(d) Clearing scenarios:

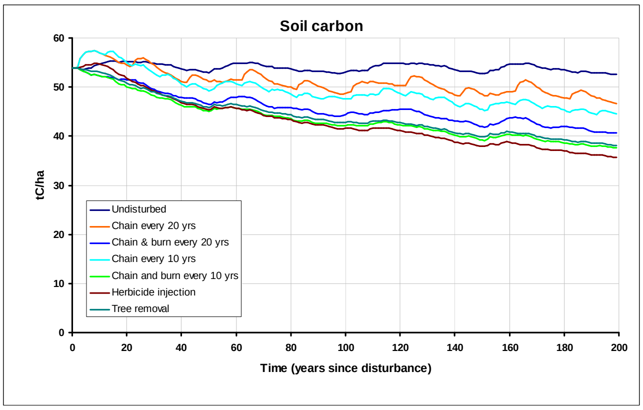


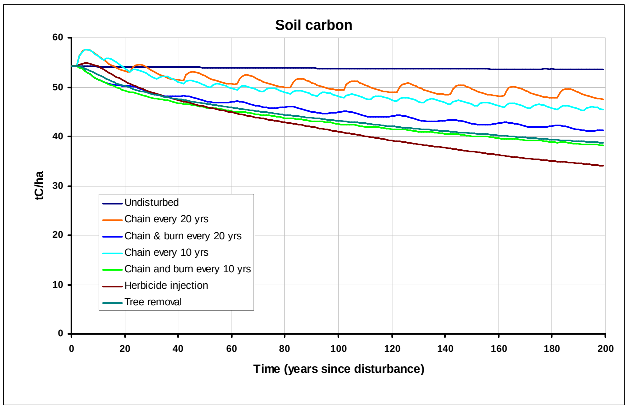
This chart summarises the trends in total ecosystem carbon with time under different management strategies (mean of 1000 simulations). This figure shows the dynamics where each treatment and each of the 1000 runs of the model were started at the same climate year. For the main analyses, summarized in the bar charts below, the starting date was randomized, to avoid any problems of initial conditions, e.g. initializing the simulations in an aberrant year. Clearing activity was initiated at year 0. To act as a point of reference, the ‘tree removal’ treatment corresponds to the complete removal of 100% of all above-ground tree biomass and immediate release to the atmosphere. The ‘herbicide’ line shows the impact of converting the tree biomass to standing dead litter (‘stags’). The curve shows eventual loss of this pool after about 140 years. The remaining curves show two frequencies of chaining (every 10 and 20 years), with and without subsequent burning of the pulled material.

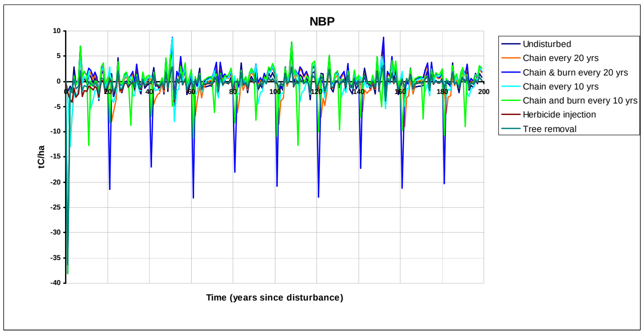
Similar trends for runs with a random start date are shown below, making the impacts of the disturbances more obvious:

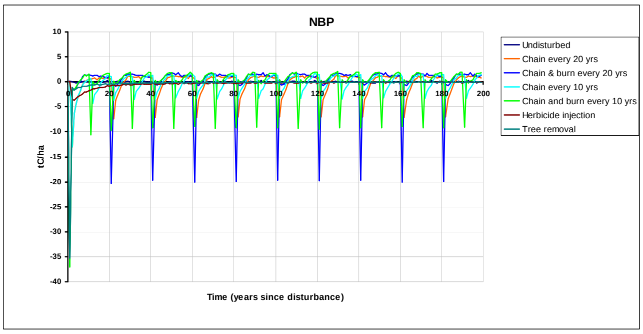


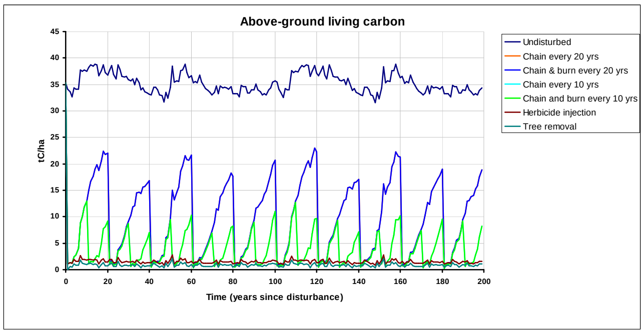
Similar sets of charts for other major pools follow, with the constant start date on the LHS, and randomized start date on the RHS:

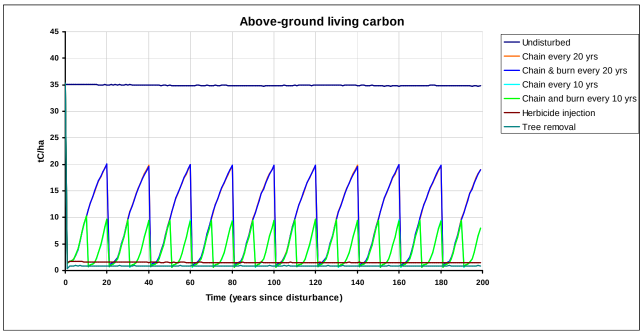


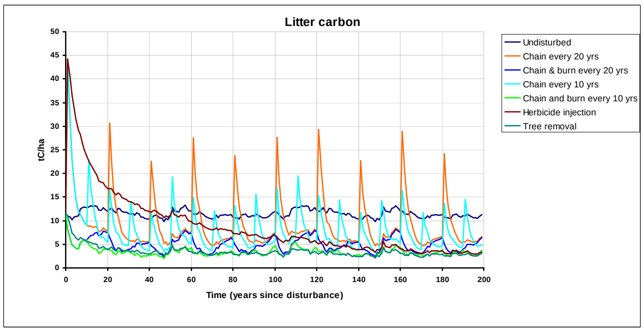


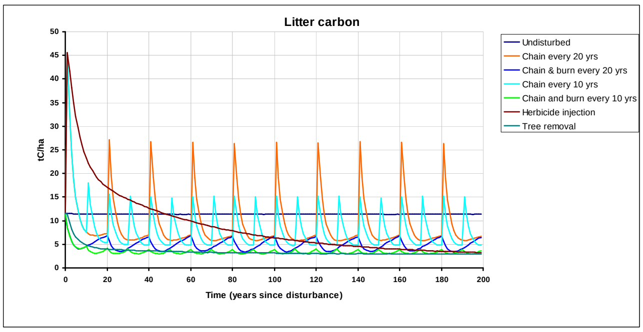




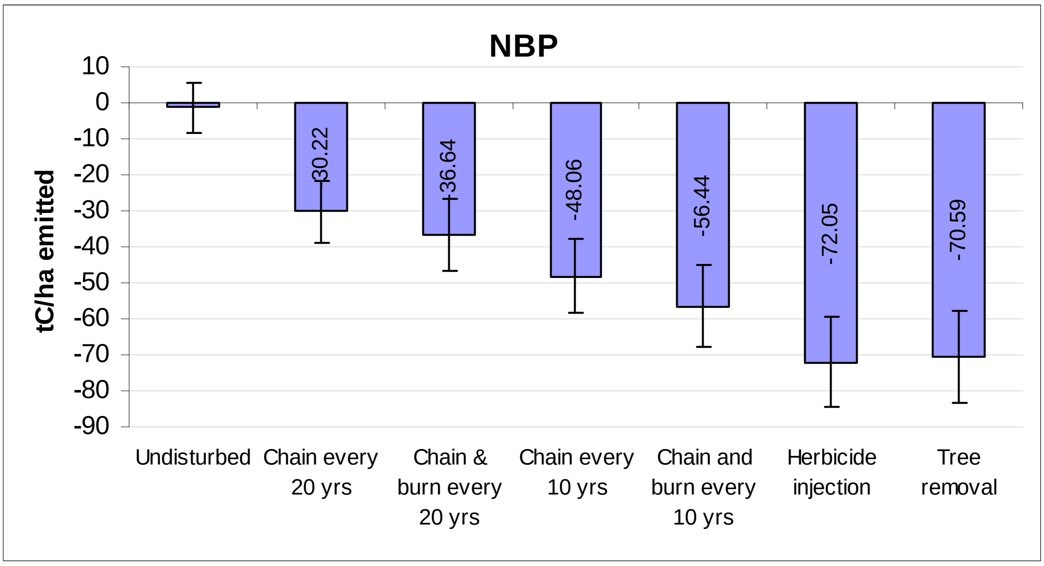


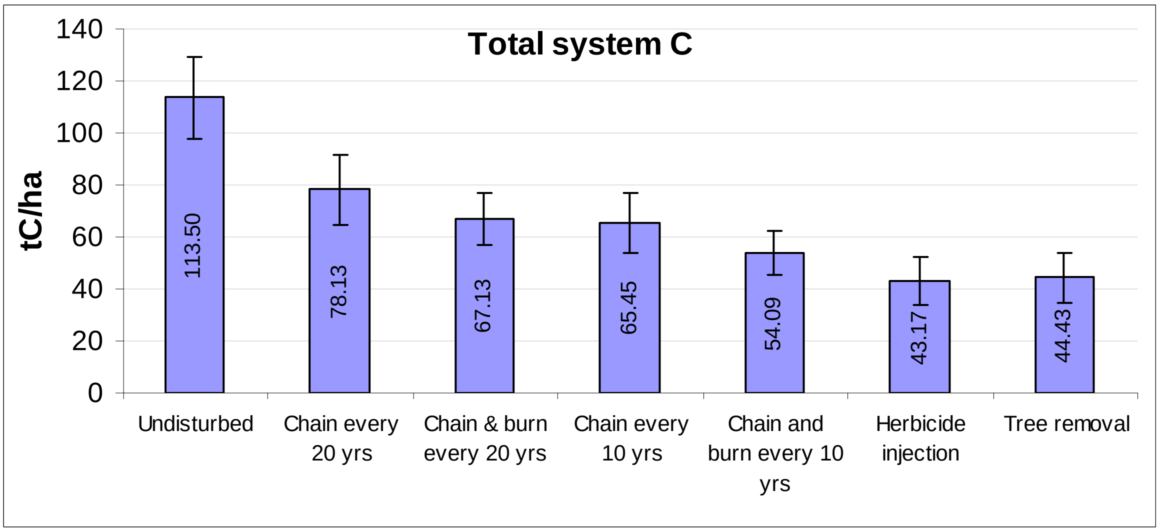


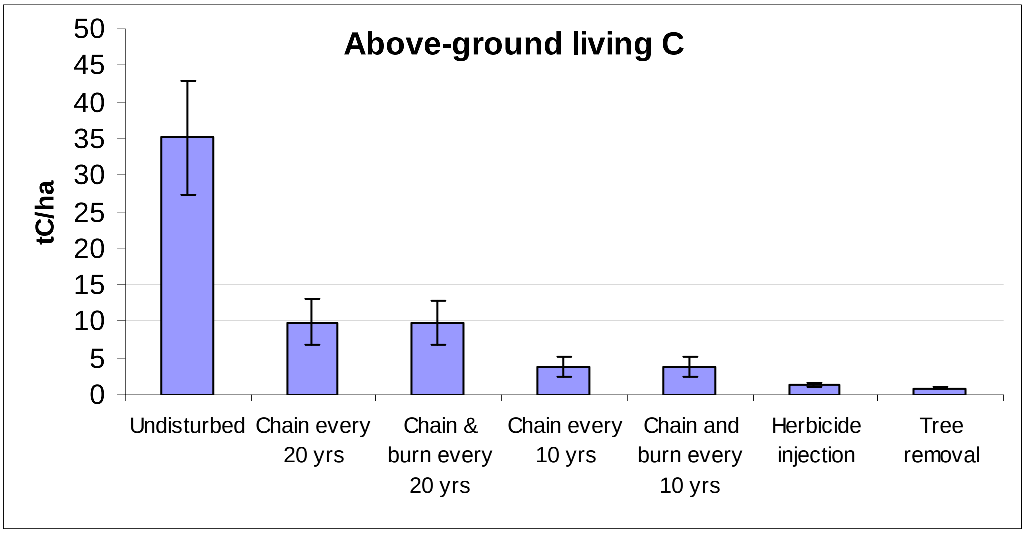


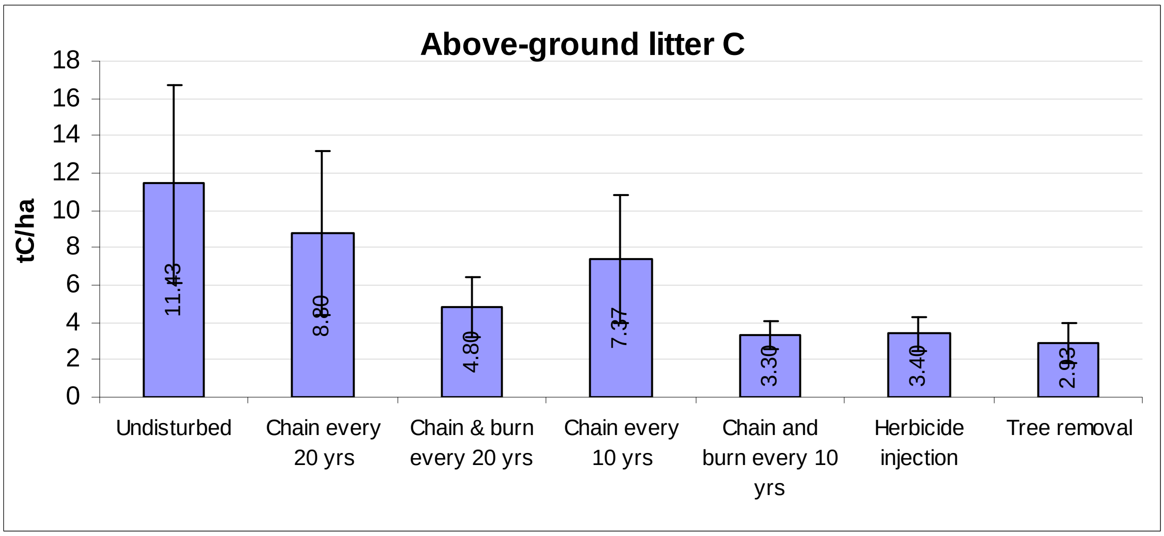


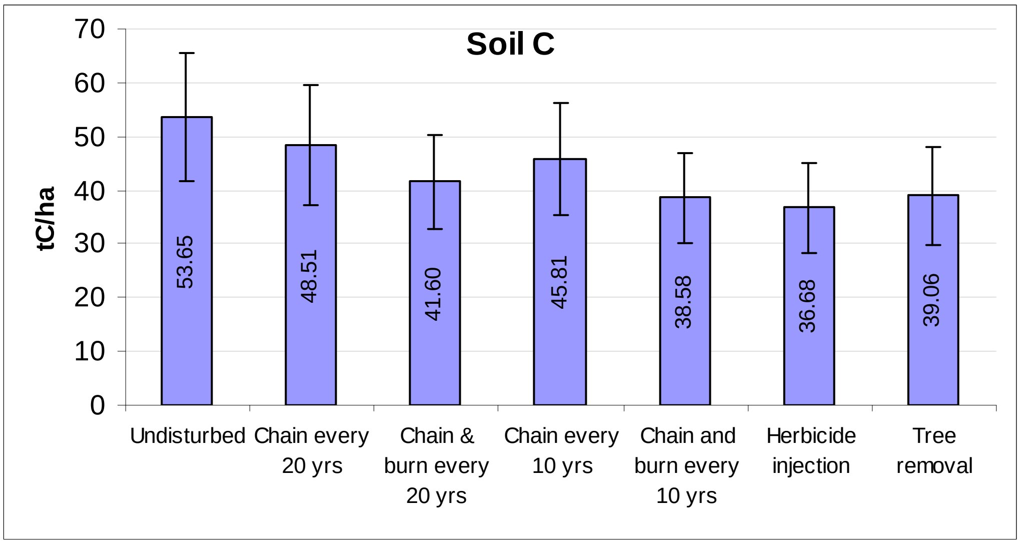
Summary results:
The results below represent a summary of the overall analysis. The NBP figure shows the net emissions over the two hundred years of the simulation for each treatment. The remaining figures are the mean carbon stocks over the last 20 years of the simulation. The error bars are 95% confidence intervals derived from 1000 simulations for each treatment.

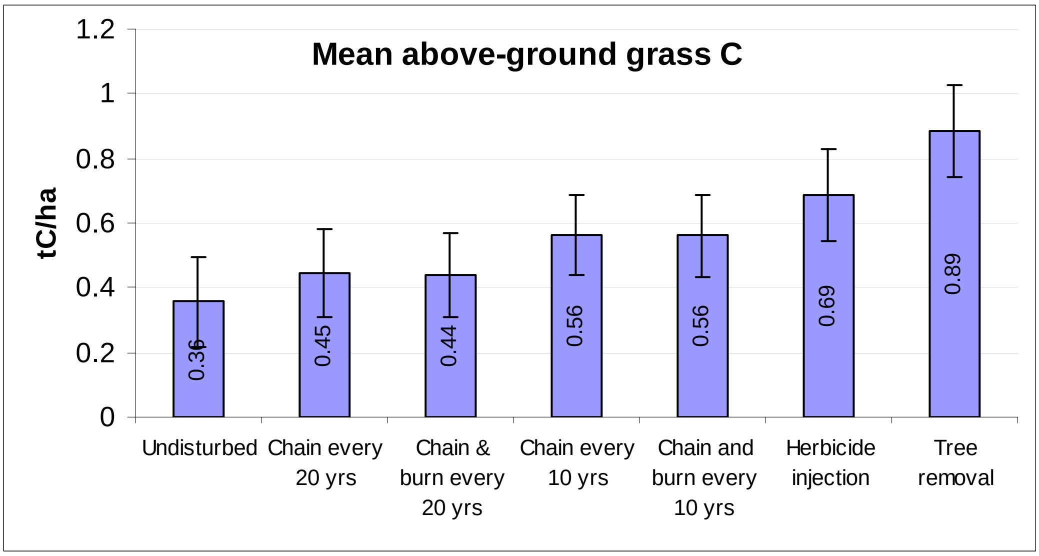



Total system C
tC/ha
140
120
100
80
60
40
20
0
113.50
78.13
67.13
65.45
54.09
43.17
44.43
Undisturbed
Chain every 20 yrs
Chain & burn every 20 yrs
Chain every 10 yrs
Chain and burn every 10 yrs
Herbicide injection
Tree removal


Above-ground living C
tC/ha
50
45
40
35
30
25
20
15
10
5
0
Undisturbed
Chain every 20 yrs
Chain & burn every 20 yrs
Chain every 10 yrs
Chain and burn every 10 yrs
Herbicide injection
Tree removal


Above-ground litter C
tC/ha
18
16
14
12
10
8
6
4
2
0
11.43
8.80
4.80
7.37
3.30
3.40
2.93
Undisturbed
Chain every 20 yrs
Chain & burn every 20 yrs
Chain every 10 yrs
Chain and burn every 10 yrs
Herbicide injection
Tree removal





Discussion

Well, not much to discuss really. My dead cat could have predicted the overall trends. The value of the work is in providing some quantitative numbers for these different clearing treatments, and in providing a simulation tool to do these sorts of analyses.

References

Burrows, W.H., Carter, J.O., Scanlan, J.C. and Anderson, E.R., 1990. Management of savannas for livestock production in north-east Australia:contrasts across the tree-grass continuum. Journal of Biogeography, 17: 503-512.

Burrows, D.M. and Burrows, W.H., 1992. Seed production and litter fall in some Eucalypt communities in central Queensland. Australian Journal of Botany, 40: 389-403.

Burrows, W.H., Henry, B.K., Back, P.V., Hoffmann, M.B., Tait, L.J., Anderson, E.R., Menke, N., Danaher, T., Carter, J.O. and McKeon, G.M., 2002. Growth and carbon stock change in eucalypt woodlands in northeast Australia: ecological and greenhouse sink implications. Glob. Change Biol, 8: 769-784.

Burrows, W.H., Hoffmann, M.B., Compton, J.F., Back, P.V. and Tait, L.J., 2000. Allometric relationships and community biomass estimates for some dominant eucalypts in Central Queensland woodlands. Australian Journal of Botany, 48: 707-714.

Grigg, A.H. and Mulligan, D.R., 1999. Litterfall from two eucalypt woodlands in central Queensland. Australian Journal of Ecology, 24: 662-664.

Harms, B. and Dalal, R., 2003. Paired-Site Sampling for Soil Carbon Estimation - Queensland, Australian Greenhouse Office, Canberra.

Hill, M.J., Roxburgh, S.H., Carter, J.O., McKeon, G.M., Barrett, D.R. (2005, submitted). Carbon dynamics in response to grazing, drought and fire in savanna woodlands of Australia: a scenario approach using 100 years of synthetic annual fire and grassland dynamics. *Australian Journal of Botany*.

Klein Goldeweijk, K., van Minnen, J.G., Kreileman, G.J.J., Vloedbeld, M. and Leemans, R., 1994. Simulation of the carbon flux between the terrestrial environment and the atmosphere. Water, Air and Soil Pollution, 76: 199-230.

Lee, K.E. and Corell, R.L., 1978. Litter fall and its relationship to nutrient cycling in a South Australian dry sclerophyll forest. Australian Journal of Ecology, 3: 243-252.

Houerou, L., 1984. Rain use efficiency: a unifying concept in arid-land ecology. Journal of Arid Environments, 7: 213-247.

Ludwig, J.A., Eager, R.W., Liedloff, A.C., McCosker, J.C., Hannah, D., Thurgate, N.Y., Woinarski, J.C.Z. and Catterall, C.P., 2000. Clearing and grazing impacts on vegetation patch structures and fauna counts in eucalypt woodland, central Queensland. Pacific Conservation Biology, 6: 254-272.

Michalewicz, Z., 1992. Genetic algorithms + data structures = evolution programs. Springer-Verlag, Berlin.

Press, W.H., Flannery, B.P., Teukolsky, S.A. and Vetterling, W.T., 1986. Numerical Recipes: the art of scientific computing. Cambridge University Press, Cambridge.

Pressland, A.J., 1982. Litter production and decomposition from an overstorey of *Euclayptus* spp. on two catchments in the New England region of N.S.W. Australian Journal of Ecology, 7: 171-180.

Roxburgh, S.H. (2004). The CASS terrestrial carbon cycle model – user guide and tutorial exercises. *CRC for Greenhouse Accounting technical report.* 43pp. http://www.greenhouse.crc.org.au/calculators/cass/

Roxburgh, S.H. and Davies, I.D., 2005. COINS, an integrative modelling shell for carbon accounting and general ecological analysis. Environmental Modelling and Software, In Press.

Roxburgh, S.H., Mackey, B.G. Dean, C. Randall, L. Lee, A., Austin, J. (2005). Soil attributes for simulation modelling of terrestrial carbon accounts: a case study in the subtropical woodlands/open forests of the Brigalow Belt, Queensland. The Rangeland Journal.

Roxburgh, S.H., Barrett, D.J., Berry, S.L., Carter, J.O., Davies, I.D., Gifford, R.M., Kirschbaum, M.U.E., McBeth, B.P., Noble, I.R., Parton, W.G., Raupach, M.R. and Roderick, M.L., 2004. A critical overview of model estimates of net primary productivity for the Australian continent. Funct. Plant Biol, 31: 1043-1059.

Skjemstad, J.O., Spouncer, L.R., Cowie, B. and Swift, R.S., 2004. Calibration of the Rothamsted organic carbon turnover model (RothC ver. 26.3), using measurable soil organic carbon pools. Aust. J. Soil Res, 42: 79-88.

Walker, J., Moore, R.M. and Robertson, J.A., 1972. herbage response to tree and shrub thinning in *Eucalyptus populnea* shrub woodlands. Australian journal of Agricultural Research, 23: 405-410.

Walker, J., 1981. Fuel dynamics in Australian vegetation. In: A.M. Gill, R.H. Groves and I.R. Noble (Editors), Fire and the Australian Biota. Australian Acadamy of Sciences, Canberra.

Walker, J., Robertson, J.A., Penridge, L.K. and Sharpe, P.J.H., 1986. herbage response to tree thinning in a *Eucalyptus creba* woodland. Australian Journal of Ecology, 11: 135-140.

Woldendorp, G., Spencer, R.D., Keenan, R.J. and Barry, S., 2002. An analysis of sampling methods for coarse woody debris in Australian forest ecosystems., Bureau of Rural Sciences, Canberra.