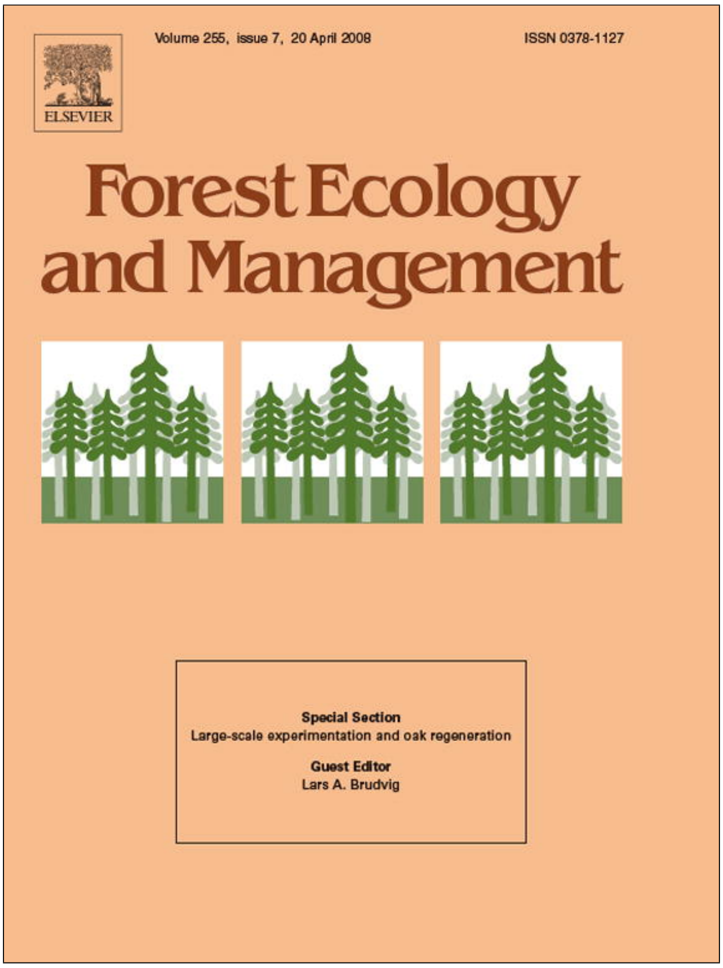
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Effects of harvest management practices on forest biomass and soil carbon in eucalypt forests in New South Wales, Australia: Simulations with the forest succession model LINKAGES

Kemachandra Ranatunga [a,*], Rodney J. Keenan [b], Stan D. Wullschleger [c], Wilfred M. Post [c], M. Lynn Tharp [c]

[a] *Bureau of Rural Sciences and CRC for Greenhouse Accounting, Department of Agriculture, Fisheries and Forestry, GPO Box 858, Canberra, ACT 2601, Australia*
[b] *School of Forest and Ecosystem Science, University of Melbourne, Water Street, Creswick, Victoria 3363, Australia*
[c] *Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6422, USA*

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Abstract

Understanding long-term changes in forest ecosystem carbon stocks under forest management practices such as timber harvesting is important for assessing the contribution of forests to the global carbon cycle. Harvesting effects are complicated by the amount, type, and condition of residue left on-site, the decomposition rate of this residue, the incorporation of residue into soil organic matter and the rate of new detritus input to the forest floor from regrowing vegetation. In an attempt to address these complexities, the forest succession model LINKAGES was used to assess the production of aboveground biomass, detritus, and soil carbon stocks in native *Eucalyptus* forests as influenced by five harvest management practices in New South Wales, Australia. The original decomposition sub-routines of LINKAGES were modified by adding components of the Rothamsted (RothC) soil organic matter turnover model. Simulation results using the new model were compared to data from long-term forest inventory plots. Good agreement was observed between simulated and measured above-ground biomass, but mixed results were obtained for basal area. Harvesting operations examined included removing trees for quota sawlogs (QSL, DBH >80 cm), integrated sawlogs (ISL, DBH >20 cm) and whole-tree harvesting in integrated sawlogs (WTH). We also examined the impact of different cutting cycles (20, 50 or 80 years) and intensities (removing 20, 50 or 80 m^3). Generally medium and high intensities of shorter cutting cycles in sawlog harvesting systems produced considerably higher soil carbon values compared to no harvesting. On average, soil carbon was 2–9% lower in whole-tree harvest simulations whereas in sawlog harvest simulations soil carbon was 5–17% higher than in no harvesting.

Keywords: Forest biomass; Carbon cycle; Harvesting; Disturbance; Gap models; Soil carbon

1. Introduction

Carbon cycles through forests in living vegetation, detritus and soil. Levels of carbon stock and rates of cycling vary considerably with site factors (climate, topography and geology), species composition and natural disturbance and management history. Regional and global inventory analyses and computer simulations indicate that the capacity of forest stands to store carbon is large (Banfield et al., 2002). Dixon et al. (1994) estimated that forest ecosystems contain approximately half of the total terrestrial carbon pool, with two-thirds of this residing in forest soil.

Despite more comprehensive inventory and modeling studies, many aspects of forest carbon cycling remain unresolved. For example, while little doubt exists regarding higher carbon stocks in forest ecosystems compared to other land cover types, the effect of management on carbon stocks and fluxes in forests is less certain. Changing species composition, harvest management practices, rotation length, fire, and other biotic and abiotic disturbances can all have important impacts on carbon stocks and fluxes. Furthermore, long-term effects are complicated by the legacy of residues left on-site at harvest, the type and condition of these residues, the natural decomposition rate of harvest residue and the rate of

* Corresponding author. Tel.: +61 2 6272 5352; fax: +61 2 6272 5827.
E-mail address: Kema.Ranatunga@brs.gov.au (K. Ranatunga).

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new detritus input to the forest floor from regrowing vegetation (Johnson, 1992; Johnson and Curtis, 2001). There is no simple relationship between the amount of timber harvested from a forest and the amount of carbon stored. Management regimes that maintain a continuous canopy cover and mimic, to some extent, regular natural forest disturbance could achieve the best combination of high wood yield and carbon storage (Thornley and Cannell, 2000).

One approach to estimating carbon dynamics for managed stands is to combine measured forest inventory data with growth models. Individual-based models of forest succession represent an important tool for examining the potential interactions among species composition, harvest operations, and residue management on carbon stored in biomass and soils. In this study, the model LINKAGES (Pastor and Post, 1985) was used to examine carbon sequestration in *Eucalyptus*-dominated forest stands of eastern Australia. The simple representation of soil carbon (SC) dynamics used in the original version of this model was replaced with a more mechanistic description of SC turnover and then used to investigate the influence of several harvest management practices on carbon sequestration. Given existing logging operations commonly used in this area of Australia, our analyses focused on single-tree selection methods of logging where the primary interest is in the production of high-quality sawlogs.

The aim of the study was to analyse impacts of different harvesting cycles and intensities on ecosystem carbon stocks. We based simulations on existing management practices, single tree and small gap harvesting as a starting point and considered more intensive practices that could have greater impacts on carbon stocks.

2. Materials and methods

2.1. Site description and forest inventory data

The effect of harvest regime on aboveground biomass (AGB) and SC stocks were simulated for Kendall State Forest in New South Wales. Kendall State Forest is located near Newcastle in New South Wales (NSW). The site is a native forest of composed various *Eucalyptus* species, dominated largely by blackbutt (*Eucalyptus pilularis* Smith). Other species include tallowood (*E. microcorys*), Sydney bluegum (*E. saligna*), turpentine (*Syncarpia glomulifera*) and bloodwood species (mainly *E. intermedia*). Forest age is not known, but individual trees can live over 400 years. Mean annual precipitation is approximately 1400 mm and mean annual temperature is 18.1 °C. There are number of soil types found at Kendall including Black earth, Chocolate soils, Red earth and Red and yellow podsolics (Isbell, 1996).

Inventory data used in this analysis were gathered from the Kendall Continuous Forest Inventory (Kendall CFI) database. Kendall CFI was established in 1960 and inventory data have since been collected every 5 years. Of the 144 permanent plots in the Kendall CFI, 18 are blackbutt-dominated. Trees within each of four circular sub-plots were counted and measured to determine stems per unit area and size class distribution for each species. Areas covered by four circular sub-plots from the inner plot to the outer plot are 0.04, 0.1, 0.2 and 0.4 ha respectively. Basal area for each tree was calculated from measured stem circumference. Trees in the following DBH classes were recorded: 10–30 cm, 30–50 cm, 50–80 cm, and trees >80 cm. Saplings <10 cm in DBH are not included in the CFI database. More details related to collection of inventory data can be found in Muhairwe (1998).

2.2. Model description

The LINKAGES model is a derivative of the JABOWA/FORET class of forest simulation models (Botkin et al., 1972; Shugart, 1984). It predicts the long-term dynamics and structure of forest ecosystems, as constrained by nitrogen availability, climate, and soil moisture. The model has been described and simulation results compared favorably to independent data on species composition, biomass, net primary productivity, soil organic matter, and nitrogen availability in many different areas (Pastor and Post, 1986; Pastor et al., 1987; Keenan et al., 1993; Post and Pastor, 1996; He et al., 1999; Hall and Hollinger, 2000). LINKAGES differs from other gap models in that it includes explicit decomposition, mineralization, and soil moisture sub-routines, allowing water and nutrient cycles to interact with species composition. It differs from other forest carbon models in that it simulates the growth of individual trees and therefore allows for analysis of inter-species composition and competition and the assessment of the impacts of different disturbance options such as timber harvesting. The stochastic nature of different processes in these types of models means that replicate analysis is required for an adequate description of variation in species composition and forest structure (Yamamoto, 1992). In this study 100 replicate simulations were conducted for each type of treatment.

2.2.1. Modification to soil carbon dynamics in LINKAGES

As originally implemented by Pastor and Post (1986), litter decomposition in LINKAGES was a function of litter input, litter quality (i.e., lignin-to-nitrogen ratio), and evapotranspiration. To improve predictions of SC sequestration for the purpose of this paper, the single soil compartment in LINKAGES was replaced with the RothC (Jenkinson, 1990). This model simulates the behavior of soil organic matter by dividing it into five compartments (Fig. 1). Each compartment decomposes at a characteristic rate as described by a first-order process, with turnover times ranging from several months to over 1000 years.

In this version of LINKAGES, decomposition of aboveground organic matter (i.e., leaf, large and small wood) remains as before – litter cohorts are tracked separately until they reach a critical C/N ratio at which point they are added to a soil pool with dynamics determined by RothC algorithms. In RothC, decomposable plant matter (DPM) and resistant plant material (RPM), represent organic matter (i.e., litter) inputs from both above- and below-ground plant parts. In our modification only fine roots contribute to RPM and DPM. Aboveground litter and

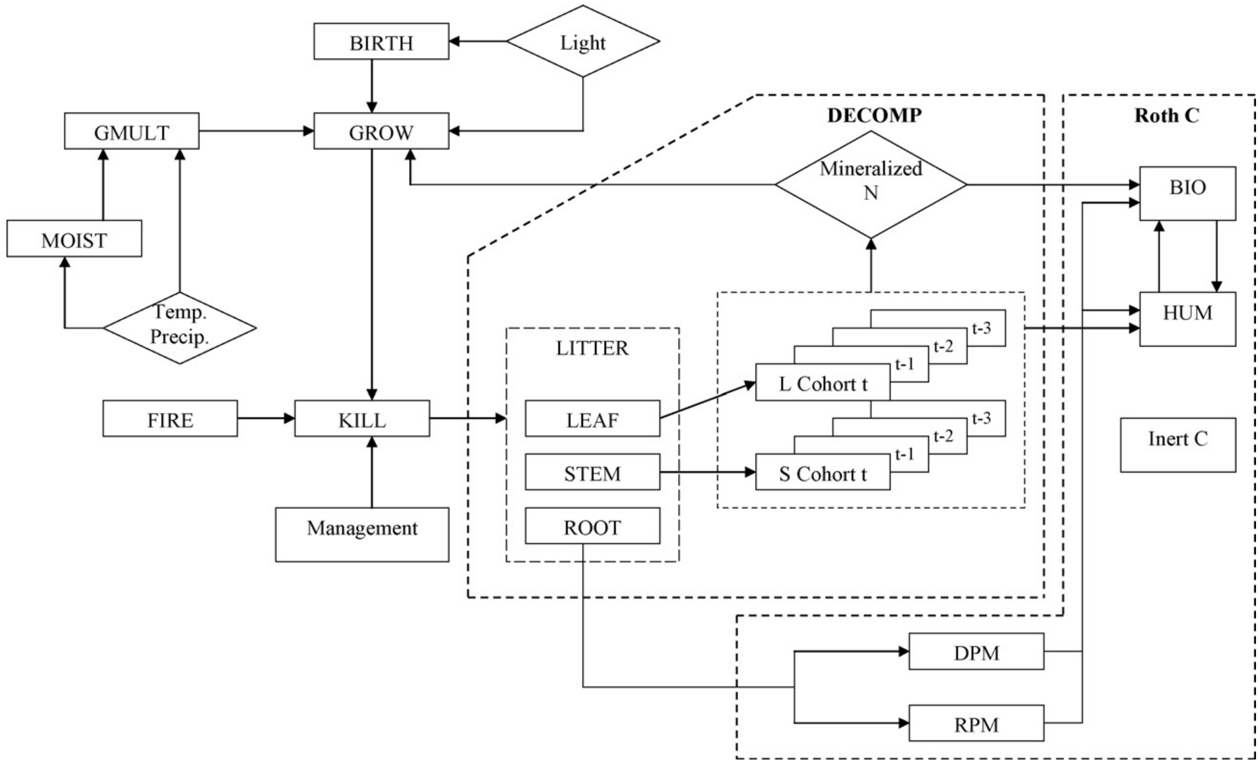

Fig. 1. Schematic diagram of new LINKAGES after incorporating RothC.

coarse woody debris (CWD) is kept separate in litter cohorts until a critical C/N ratio is reached for each litter type and then it is added directly to the soil HUM pool. Incoming organic matter from roots passes through the DPM and RPM compartments once. DPM and RPM partially decompose into carbon dioxide, which is lost from the system. Remaining DPM and RPM are transferred to microbial biomass (BIO) and humified organic matter (HUM). The soil is assumed to contain an amount of organic matter that is inert to biological decomposition (IOM). In the case of simulations conducted here, the IOM compartment is set to zero since it will not change over the simulations.

While each of the five compartments in RothC decomposes at their own characteristic rate, the rates are modified by environmental factors, which include temperature, soil water deficit, and a plant protection factor. The temperature function is:

$$f(T_m) = \frac{47.9}{1 + \exp((106/T_m) + 18.3)} \quad (1)$$

where T_m is monthly temperature (°C). This function has the value of 1.0 at 9.25 °C, the mean annual temperature at Rothamsted where the nominal decomposition rate parameters were originally fitted to field experiments. The soil moisture deficit factor varies from 0 to 1.0 depending on soil water potential. It is 1.0 for potentials ranging from field capacity to soil water potential of −100 kPa. At this point, soil moisture function decreases linearly from 1.0 at −100 kPa to 0.2 at a soil water potential of −1500 kPa. The plant protection factor has two values in the RothC model; 1.0 for when plants are dormant, and 0.6 when plants are actively growing. This factor was set at 0.6 for all simulations with LINKAGES.

Nitrogen mineralization and carbon turnover rates of leaf and woody litter are modeled in LINKAGES using litter quality (lignin and nitrogen content) and environmental conditions. Annual percent weight loss of each cohort is calculated as a function of actual evapotranspiration and current lignin:nitrogen ratio and a factor that increases decomposition rate when leaf area is reduced due to disturbance or mortality and there is higher temperature at the forest floor. Total weight loss is restrained to 10%/year for wood from trees <10 cm dbh, 3%/year for wood >10 cm dbh, 5% for well-decayed wood, and <20% for twigs. Nitrogen and lignin contents change during the decomposition process as described by Aber and Melillo (1982). The new nitrogen concentration is calculated after adding in and subtracting weight loss. When the critical percent of nitrogen is reached, cohort organic matter and nitrogen contents are transferred to humus organic matter and nitrogen. Woody litter is first transferred to a well-decayed wood cohort where it resides until it reaches a second critical percent of nitrogen; whereupon it is then transferred to humus (Fig. 1, Appendix A). If the critical percent of nitrogen is not reached, the cohort is retained for an additional year of decomposition, and the weight, nitrogen content, and lignin concentration are updated.

2.2.2. *Nitrogen modifications*

Nitrogen, not a part of RothC formation, is tracked in LINKAGES. Roots are assigned a C/N ratio of 51. DPM is assumed to have an N concentration three times that of RPM. DPM and RPM therefore have C/N ratios of 38.25 and 12.75 respectively (Kayhanian and Tchohanoglous, 1992). Microbial biomass, BIO is assumed to have a C/N ratio of 8.5 and when organic matter is transferred, sufficient N is immobilized from the available N pool to meet the BIO growth demand. If not enough N is available, decomposition of RPM, DPM and HUM pools is reduced. The C/N ratio of the HUM pool varies depending on the N content of incoming materials. When each of soil organic matter pools decomposes an amount of N is transferred to the available N pool based on the current C/N ratio of the contributing pool.

2.2.3. Harvest management practices

LINKAGES was modified to accommodate three harvest regimes, each of which depends on the type of timber required. Trees are harvested mainly for quota sawlogs (QSL, DBH >80 cm), and integrated sawlogs (ISL, DBH >20 cm). In ISL harvesting, trees are randomly harvested in the model until the harvest intensity ($m^3\ ha^{-1}$) is met, whereas QSL are harvested in successive cutting cycles. Whole-tree harvesting (WTH) is not normally practiced in Australia but was tested to assess the impact of higher intensities of harvesting. In this treatment leaves, bark and branches were removed from the forest along with the tree boles. Harvest requirements are read in the main program and then stems are transferred to the KILL sub-routine in LINKAGES to remove trees from the plot, based on the type of harvest operation being simulated. Trees to be cut were selected in the model in sequential order beginning with the largest DBH within each harvest class. Harvest volumes were converted to total biomass (Mg/ha) based on species-specific estimates of wood density. Woody litter (i.e., harvest residue) left on the site following simulated harvest operations was calculated by subtracting harvested biomass from total tree biomass.

2.2.4. Plot size and light function

The original version of LINKAGES simulates, on a yearly cycle, the establishment, growth, and mortality of all trees in a 1/12 ha plot (0.083 ha). This small plot size is to capture successional dynamics in the gap created by one large, mature tree (Shugart and West, 1979). To provide for simulation of the different harvesting options, the size of plot was increased to 1 ha. While this adjustment may alter the nature of species replacement sequences resulting from gap-phase processes, this is not critical for our consideration of managed forests that are subject to larger scale disturbances. This adjustment also had implications for estimation of light penetration at different levels in the canopy. Further, Hall and Hollinger (2000) stated that the original LINKAGES underestimates the light availability in predominantly evergreen forests with high specific leaf mass, in contrast to the deciduous eastern North American forests. Since eucalypt forests are evergreen and have high specific leaf mass, the light function was changed to accommodate these differences in line with Hall and Hollinger (2000).

2.2.5. Biomass function

Biomass equations for wood, stem bark, branch and leaf were incorporated for the *Eucalyptus* species in this forest (Bi et al., 2004) according to the following model:

$$Y_i = \exp(\beta_i^1 + \beta_i^2 \ln D) + \varepsilon_i$$

where Y_i represents biomass for each component. D represents overbark diameter at breast height. β_i^1 and β_i^2 are coefficients for each component and given in Appendix B. The stem volume (V) equation employed was from Muhairwe (1999):

$$V = e^{b_0}\mathrm{DBH}^{b_1}\left[\frac{H^2}{H-1.3}\right]^{b_2}$$

where e is the exponent (approximately equal to 2.718281828); $b_0 = -10.595765$; $b_1 = 1.949423$ and $b_2 = 1.047541$. Height profile function for leaf mass was also adopted from Muhairwe (1999);

$$H = 1.3 + \left[b_3 + \frac{b_4}{\mathrm{DBH}}\right]^{-2.5}$$

where H is the height of the tree (m), $b_3 = 0.202856$ and $b_4 = 1.861070$.

2.3. Model parameterization

There are 23 parameters required for each species in the new version of LINKAGES (Appendix B). Minimum growing degree days (D_{min}) and maximum growing degree days (D_{max}) were estimated from species distribution maps of Australia (Boland et al., 1992) aided by an equation predicting degree days as a function of latitude and altitude (Shugart and Noble, 1981). JABOWA growth curve was used to estimate tree species growth parameters such as growth scaling parameters (B2 and B3) and scalar for species maximum diameter increment (G). In growth curve-fitting, the parameters such as maximum age (MaxAGE in years), maximum DBH (MaxDBH in cm) and maximum height (MaxHT in cm) are specified. Values for biomass coefficients (β_i^1 and β_i^2 and i being stem (s), stem bark (k), branch (b) and foliage (f)) are taken from Bi et al. (2004). Decomposition parameters used for *Eucalyptus* species are given in Appendix A.

2.4. Model evaluation and simulation scenarios for harvest

NSW forest inventories do not provide a direct measure of AGB. Plot-specific and mean values of basal area, stem density, and aboveground biomass (based on the equations described above) for 18 CFI plots are given in Appendix C. No measured data were available on carbon stocks in woody debris, forest floor, or soil. Since there was no calibration data for these components of the ecosystem, results from the scenarios are an initial analysis of the impacts of harvesting that can be used as a basis for further investigation and hypothesis testing.

Of the 18 blackbutt-dominated plots, detailed records on the total amount of timber removed since 1960 exist for only three plots (#85, #296 and #326) (Appendix D). Simulations of basal area and aboveground biomass by LINKAGES were compared with these three plots and a plot (512) where no logging operations had been conducted in the past 40 years. These harvesting records were used as input to the simulations.

Several simulations were conducted to examine long-term changes of SC stocks under QSL and ISL. For changing harvesting cycle, WTH is also considered. Two types of harvest management scenarios for each harvesting system were examined. The first varied harvest intensities from 20, 50 and 80 $m^3 ha^{-1}$ in 20-, 50- and 80-year cutting cycles for both QSL and ISL harvest systems. The second varied the harvest cycle from 20, 50, and 80 years holding harvest intensity constant at 100 $m^3 ha^{-1}$. A comparative analysis of SC dynamics with and without harvestings was also conducted.

In all simulations, LINKAGES was run for 1000 years with long-term monthly averages and standard deviations for both temperature and precipitation. Steady state behavior in the model was typically observed after 500–600 years. Harvest operations were initiated after 700 years for long-term simulations. No other disturbances, for example fire, insect pests or storm damage were simulated.

3. Results

3.1. Comparison of model output with measured data

Output from LINKAGES was compared with measured basal area and aboveground biomass for four CFI plots. Simulated basal area was in reasonable agreement with measured values (Fig. 2); however, the model tended to overestimate basal area for those plots where logging operations had taken place in the last 40 years (plots #85, #296, and #326), whereas simulated basal area in plot #512 was slightly underestimated. Simulated aboveground biomass was also in reasonable agreement with measured biomass in plots #326 and #512, while simulated aboveground biomass in plots #85 and #296 followed similar temporal trends to measured biomass, although actual differences were up ±75 Mg/ha (Fig. 2). Some of these discrepancies are due to problems associated with the spatial scale of the simulations compared to the scale that harvest records were compiled. Unrecorded harvesting before 1960 may have also contributed to this discrepancy.

With no harvesting disturbances, LINKAGES reaches steady biomass, litter, and SC pools after 500–600 years of simulation. AGB, CWD, SC and total carbon (TC) are around 430, 90, 115 and 370 Mg/ha respectively for *E. pillularis* dominated blackbutt forests in NSW (Fig. 3). AGB and CWD are converted to carbon and added with SC to estimate TC. Therefore, the estimation of TC does not include root and fine surface litter. Simulated SC levels in this study are generally in agreement with other published sources for temperate eucalypt forest (Dixon et al., 1999; Bauhus et al., 2002).

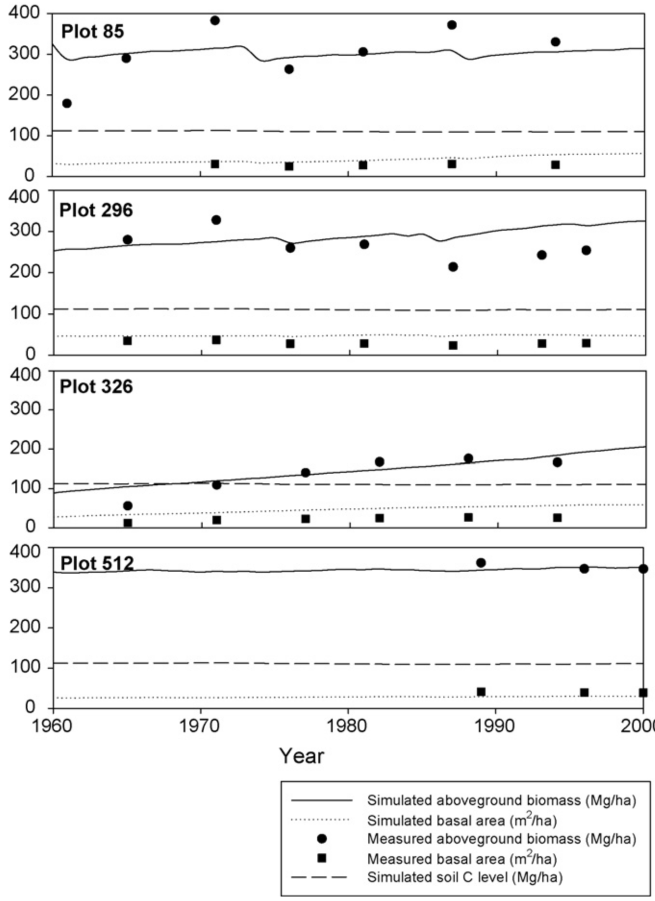

Fig. 2. Comparison of LINKAGES simulation outputs with measured basal area distribution and aboveground biomass. Simulated stem density, coarse woody debris and soil carbon changes are also given for plot 85, 296, 326 and 512.

3.2. Effects of changing cutting cycles

The simulation showed no major impacts of cutting cycle or standard sawlog harvest system on average above-ground biomass or woody debris (Table 1). The above-ground biomass

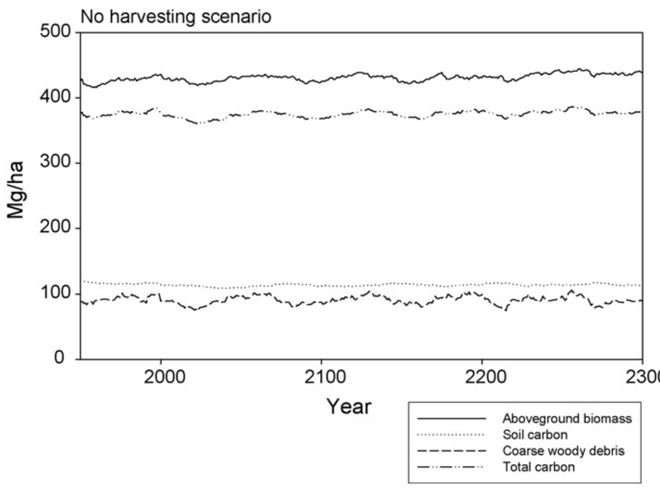

Fig. 3. Selected Linkages outputs under no harvesting operations (note that soil organic matter is presented as soil carbon).

Table 1
Long-term averages of selected Linkages outputs of all three harvesting systems for changing intensity and frequency of cutting cycles (note that soil organic matter is presented as soil carbon)

Harvesting system	Cutting cycle (years)	Harvesting intensity (m^3)		
		20	50	80
Aboveground biomass (Mg/ha)				
Quota	20	424	459	452
	50	420	446	439
	80	419	439	431
Integrated	20	432	462	448
	50	427	440	433
	80	427	433	435
Whole tree	20	408	418	408
	50	414	422	416
	80	418	426	418
Coarse woody debris (Mg/ha)				
Quota	20	96	113	113
	50	96	98	100
	80	94	95	96
Integrated	20	102	112	114
	50	98	100	100
	80	98	96	97
Whole tree	20	85	88	85
	50	88	91	89
	80	91	92	91
Soil carbon (Mg/ha)				
Quota	20	115	126	125
	50	114	117	119
	80	114	116	117
Integrated	20	115	125	125
	50	115	118	119
	80	115	116	118
Whole tree	20	105	110	106
	50	107	109	108
	80	112	108	110
Total carbon (Mg/ha)				
Quota	20	375	413	408
	50	372	389	389
	80	370	383	380
Integrated	20	382	412	406
	50	377	388	385
	80	377	381	384
Whole tree	20	351	363	352
	50	358	366	360
	80	367	367	364

for the WTH harvest system was generally lower than the other systems, probably reflecting reduced nutrient supply and corresponding reduced growth associated with removal of more labile nutrient pools. Simulated SC was generally higher with the shorter cutting cycle. This was likely to be the result of greater amounts of woody debris and foliage entering the forest floor and soil subsystem as a result of repeated disturbance. This result is similar to other modeling studies (Thornley and Cannell, 2000). We did not have sufficient data to compare sites that had not been subject to harvesting. The model simulates the growth of individual trees but output is not provided on

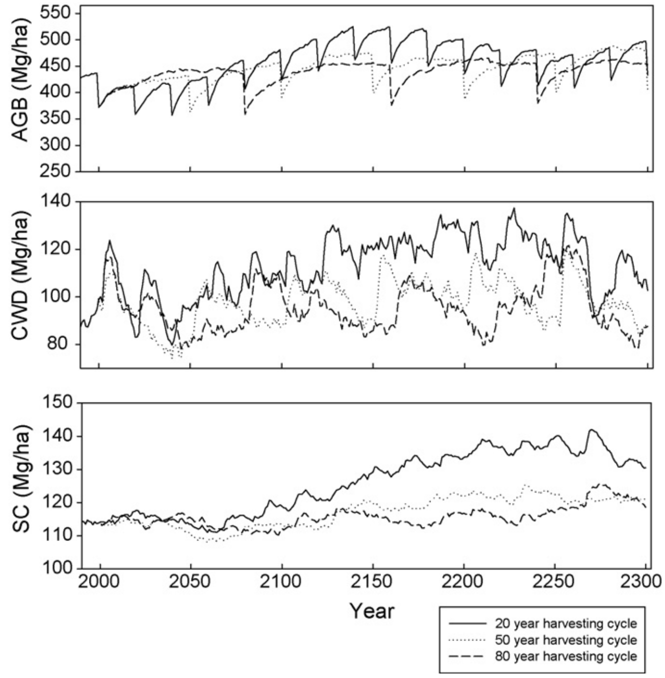

Fig. 4. Changes of aboveground biomass, coarse woody debris and soil carbon of quota sawlog system for three cutting cycles in 50 m^3 volume (note that soil organic matter is presented as soil carbon).

diameter class distribution and stand structure. Large trees can contribute substantially to total biomass (Brown et al., 1997). The model may not simulate the development of large trees in complex stands effectively and therefore may underestimate total above-ground biomass under the no harvesting option.

In both sawlog systems, AGB was higher with the short cutting cycle, particularly between 100 and 200 years of simulation (Figs. 4 and 5). This may be a result of repeated harvesting increasing the amount and intensity of incoming solar radiation reaching the soil surface. This decreases transpiration rates and interception by the forest canopy, and increases amounts of precipitation reaching and infiltrating the forest floor. This increased moisture combined with modelled increases in soil temperature with harvesting boosts the activity of soil microbes, increasing nutrient mineralization and biomass growth. Frequent harvesting also means that the stand is dominated by trees in their maximum growth phase, boosting average NPP. Further, in the short cutting cycle more small trees

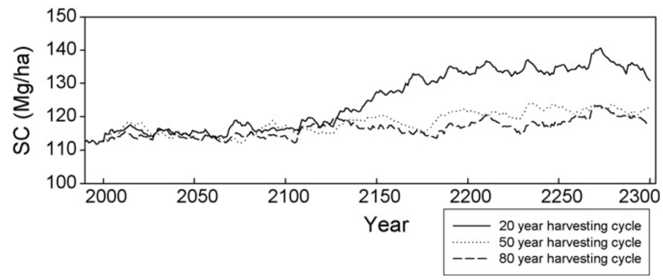

Fig. 5. Changes of aboveground biomass, coarse woody debris and soil carbon of integrated sawlog system for three cutting cycles in 50 m^3 volume (note that soil organic matter is presented as soil carbon).

are harvested than in the long and medium cycles to meet defined harvesting volumes, allowing more young trees to grow. CWD had irregular patterns in early period of the simulation, but later reached higher average levels for the short cutting cycle. In the short cycle, SC levels started increasing after the fifth harvest or 80–100 years of the simulation.

3.3. Effects of changing harvesting intensities

Both sawlog systems produced higher values of AGB, CWD, SC and TC than the WTH for all three harvesting intensities (low, 20 m^3; medium, 50 m^3; and high, 80 m^3) as shown in Table 1. Regardless of harvesting system, low intensity normally produces low values of AGB compared to medium and high intensities. Short and medium cutting cycles, and medium and high intensities produced higher values of AGB in both sawlog systems. The medium intensity produces higher values of AGB than the high intensity. Longer cutting cycle and medium intensity produced higher values of AGB in WTH system.

The mass of CWD generally followed that of AGB. Low intensity harvesting generally produced lower values of average CWD and SC compared to medium and high intensities. However, there is no substantive difference in SC between medium and high intensities for both sawlog systems. Compared to sawlog operations, low SC gains have observed in the WTH. Among operations within the WTH, longer cutting cycles produced higher values of SC and TC. High frequency of cutting and medium and high intensities have produced higher values of SC. As expected, changes of TC have a similar behavior to that of AGB, CWD and SC. Highest values of SC and TC have found in high frequency of cutting and medium intensity regardless of the type of sawlog harvesting system.

There was no substantial variation in AGB over time for the simulated low intensity operation (Figs. 6 and 7). High intensity of harvesting has produced higher AGB values in the first half of the simulation; however, the medium intensity has taken its place in the second half of the simulation. Medium level disturbance appears to have positive impacts on forest growth in long run. Considerable changes in SC occurred in the medium and high intensities after the third cutting cycle or 150 years of simulation.

3.4. Changes in soil carbon under harvesting regime compared to 'no harvesting' scenario

Comparing average SC over 300 years' in the no harvesting scenario with different cutting cycles (Table 2) showed that sawlog harvesting systems had higher SC. However, considerable variation can be found between periods. SC in the WTH system was considerably lower (2–9%) than in the harvesting operations across all cutting cycles. Differences between the no harvesting simulation and harvesting simulations were lower operation in the first 100-year period. The short cutting cycle resulted in larger quantities of SC for both sawlog systems, particularly in the latter part of the simulation. In the WTH system, SC was 9% lower than the other cutting systems for the same time period and harvesting intensity.

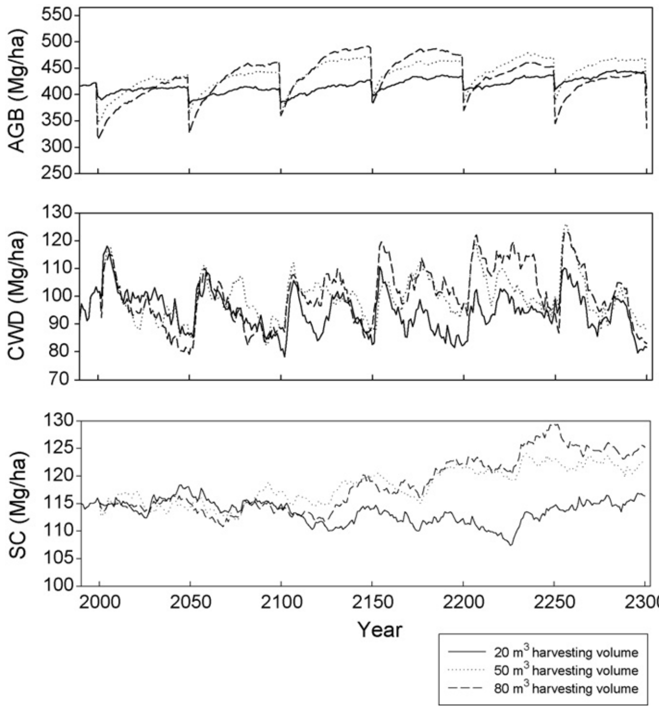

Fig. 6. Changes of aboveground biomass, coarse woody debris and soil carbon of integrated sawlog system for three harvesting volumes in 50-year cycle (note that soil organic matter is presented as soil carbon).

All three cutting cycles had higher simulated SC compared to no harvesting (Table 3), with the exception of the 20 m^3/20-year cycle. There were no substantial differences in SC between the other two cutting cycles for the same intensity. Levels of SC increased with the short cycle cutting in 50 and 80 m^3 intensities.

SC was higher under medium and high intensities of harvesting for all three cutting cycles with the short cycle of cutting having the highest levels of SC (Table 4). SC in the later 200 years of the simulation, low intensity in all cutting cycles had lower average SC compared to no harvesting.

In general, SC was 5–17% higher in sawlog harvesting systems compared with no harvesting. In the WTH system SC was 2–9% lower than no harvesting for all combinations of intensity and cutting cycles. This is consistent with the analysis of field studies by Johnson and Curtis (2001) who found that sawlog harvesting had, on average, 18% higher SC than no

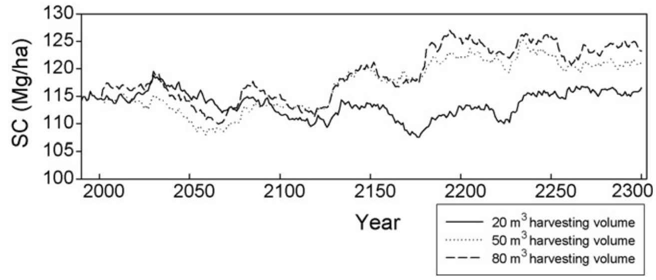

Fig. 7. Changes of aboveground biomass, coarse woody debris and soil carbon of quota sawlog system for three harvesting volumes in 50-year cycle (note that soil organic matter is presented as soil carbon).

Table 2
Percentages of SC changes with no harvesting scenario for different cutting cycles of quota sawlog, integrated sawlog and whole-tree-harvesting (WTH) systems

Simulation period (years)	Quota sawlogs			Integrated sawlogs			WTH		
	20 years	50 years	80 years	20 years	50 years	80 years	20 years	50 years	80 years
0–100	2.47	1.93	1.54	1.75	1.74	2.20	−2.33	−0.97	−0.28
101–200	9.72	2.23	2.08	8.54	2.91	3.66	−4.77	−1.82	−1.20
201–300	17.32	7.22	3.92	12.51	5.97	4.23	−9.15	−4.22	−2.90
Average	9.83	3.79	2.52	7.60	3.54	3.36	−5.42	−2.34	−1.46

Harvesting volume being 100 m^3 for all operations.

Table 3
Percentage of SC changes with respect to no harvesting scenario for different harvesting intensities of quota sawlog system

Simulation period (years)	20-year cutting cycle			50-year cutting cycle			80-year cutting cycle		
	20 m^3	50 m^3	80 m^3	20 m^3	50 m^3	80 m^3	20 m^3	50 m^3	80 m^3
0–100	1.73	2.35	1.62	2.12	−0.22	2.33	2.35	1.02	2.29
101–200	−2.90	12.15	10.00	−1.99	3.53	4.09	−0.34	1.48	2.33
201–300	−2.93	18.70	18.78	−0.05	6.07	8.18	0.02	3.44	3.97
Average	−1.37	11.07	10.13	0.03	3.13	4.87	0.68	1.98	2.86

Table 4
Percentage of SC changes with respect to no harvesting scenario for different harvesting intensities of integrated sawlog system

Simulation period (years)	20-year cutting cycle			50-year cutting cycle			80-year cutting cycle		
	20 m^3	50 m^3	80 m^3	20 m^3	50 m^3	80 m^3	20 m^3	50 m^3	80 m^3
0–100	0.66	2.86	2.13	2.48	2.42	1.62	1.65	1.44	2.22
101–200	−2.11	10.34	12.09	−1.06	3.90	3.02	−0.75	2.54	3.73
201–300	2.08	17.64	16.33	−1.29	6.25	8.63	−0.67	3.70	4.74
Average	0.21	10.28	10.18	0.05	4.19	4.42	0.08	2.56	3.56

harvesting, while soils in WTH systems had an average 6% lower SC. Shorter cutting cycles of QSL and ISL produced higher levels of SC than longer cycles while SC was lower in shorter cutting cycles than longer cutting cycles in WTH system.

4. Conclusion

This study set out to explore the impacts of different intensities and frequencies of timber harvesting on above-ground biomass, woody debris and soil carbon in eucalypt-dominated forest ecosystems in NSW, Australia using a linked soil-tree forest ecosystem simulation model. Results indicated that medium or high intensities of sawlog harvesting in shorter cutting cycles resulted in similar or higher levels of AGB and CWD and higher levels of soil carbon compared with no harvesting. On the other hand, whole-tree harvesting had considerably lower AGB, CWD and SC than either sawlog harvesting or no harvesting. On average, soil carbon was 2–9% lower with whole-tree harvesting whereas SC was 5–17% higher for sawlog harvesting systems compared to no harvest scenario.

These results are consistent with other studies in the literature and have implications for the future management of forest ecosystems to meet climate mitigation objectives. They provide a basis for further study and analysis of carbon dynamics in eucalypt forest ecosystems. A more complete understanding of carbon dynamics for native and managed *Eucalyptus* stands will require more detailed long-term monitoring of aboveground biomass, coarse woody debris, and soil carbon stocks in forests under different intensities and types of management.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2008.01.002.

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