Global Change Biology (2007) **13**, 1–14, doi: 10.1111/j.1365-2486.2007.01376.x

Development of a stable isotope index to assess decadal-scale vegetation change and application to woodlands of the Burdekin catchment, Australia

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Abstract

Forty-four study sites were established in remnant woodland in the Burdekin River catchment in tropical north-east Queensland, Australia, to assess recent (decadal) vegetation change. The aim of this study was further to evaluate whether wide-scale vegetation 'thickening' (proliferation of woody plants in formerly more open woodlands) had occurred during the last century, coinciding with significant changes in land management. Soil samples from several depth intervals were size separated into different soil organic carbon (SOC) fractions, which differed from one another by chemical composition and turnover times. Tropical (C_4) grasses dominate in the Burdekin catchment, and thus $\delta^{13}C$ analyses of SOC fractions with different turnover times can be used to assess whether the relative proportion of trees (C_3) and grasses (C_4) had changed over time. However, a method was required to permit standardized assessment of the $\delta^{13}C$ data for the individual sites within the 13 Mha catchment, which varied in soil and vegetation characteristics. Thus, an index was developed using data from three detailed study sites and global literature to standardize individual isotopic data from different soil depths and SOC fractions to reflect only the changed proportion of trees (C_3) to grasses (C_4) over decadal timescales. When applied to the 44 individual sites distributed throughout the Burdekin catchment, 64% of the sites were shown to have experienced decadal vegetation thickening, while 29% had remained stable and the remaining 7% had thinned. Thus, the development of this index enabled regional scale assessment and comparison of decadal vegetation patterns without having to rely on prior knowledge of vegetation changes or aerial photography.

Keywords: ^{13}C, Burdekin catchment, isotopes, land use, soil organic carbon, soil organic matter, tropical woodlands, turnover time, vegetation thickening

Received 22 August 2006; revised version received 9 February 2007 and accepted 20 February 2007

Introduction

Large-scale changes in vegetation, from more open to more woody systems, due to climatic alterations or modification in land management practices, can result in substantial changes in carbon stocks, expressed in the potential to sequester carbon in soil and vegetation (Scholes & van der Merwe, 1996). The role of increasing biomass in forests to offset greenhouse emissions from human activities has received particular attention (e.g. Dixon *et al*., 1994; Valentini *et al*., 2000). However, the absence of sufficient and reliable data on the timing and extent of vegetation change is a significant factor in limiting assessment of current, past and future biomass estimates (Burrows *et al*., 2002). So far, studies on gradual vegetation changes over large areas have been mostly limited to the use of aerial photography and satellite imagery, with limited use of permanent

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monitoring sites (e.g. Burrows *et al*., 2002; Fensham & Fairfax, 2002; Rogan & Chen, 2004). These techniques are able to evaluate vegetation change over large areas, but they cannot provide information for timescales of >50 years and are, therefore, limited to the most recent period of vegetation flux. In this timeframe, it is also difficult to discern whether a change in vegetation is long-term (due to climate or changed land management practices) or short-term (due to drought, disease or fire). An alternative approach employs field studies that utilize biomass and soil organic carbon (SOC) properties to determine vegetation changes that occurred over the last century and longer time scales. These studies rely on the distinctly different carbon isotopic (δ^{13}C) values between tropical grasses, employing the C_4 photosynthetic pathway (-17 to -9‰; average -14‰) and trees and shrubs (C_3 photosynthetic pathway: -32 to -22‰; average -27‰), which, once transformed into SOC, serve as a record of changes in the ratio of tree- and grass-derived organic matter input to the soil over decades, centuries to millennia (e.g. Boutton *et al*., 1998; Guillet *et al*., 2001; Jessup *et al*., 2003; Smith & Johnson, 2003; Biedenbender *et al*., 2004; Krull & Bray, 2005; Krull *et al*., 2005).

Studies by Boutton *et al*. (1998, 1999), Krull & Bray (2005) and Krull *et al*. (2005) have shown that δ^{13}C analyses of size-separated SOC can effectively be used to identify recent (<100 years) vegetation change patterns. Studies of this type are restricted to locations that are relatively uniform in terms of soil and vegetation types to ensure that changes in these variables do not confound the interpretation of isotopic values. Our aim was to develop a method that would utilize the isotopic technique on a regional scale with varying soil, vegetation and climate, which in the past could only be assessed by interpreting historical and recent aerial photography or satellite imagery.

The Burdekin catchment in tropical north Queensland, Australia, covers approximately 13 Mha, of which 87% is used for the grazing of beef cattle. Seventy-six per cent of the area is classed as remnant woodland/savanna vegetation (Accad *et al*., 2003). It includes a variety of soil and vegetation types and the climate varies from moist–humid near the coast to dry in the semi-arid interior (http://www.desertuplands.org.au/duslrad/welcome.html; DND, 1970–1973). Previous detailed isotopic studies in north-east Queensland have confirmed that thickening has occurred at specific locations over the last 50–100 years, and this has been linked to the combined possible effects of CO_2 fertilization and changed land management practices, such as fire suppression and domestic cattle grazing (Krull & Bray, 2005; Krull *et al*., 2005). The difficulty in applying the isotopic method across such a diverse area lies not only in the different δ^{13}C values among plant species, but in the sensitivity of plant isotopic fractionation to light and water availability.

Balesdent *et al*. (1993) found over 3‰ difference in δ^{13}C values of leaves from tree species within a forest, which they attributed to variability in local climate. Similarly, Garten *et al*. (2000) observed a large influence of climate and litter quality on soil δ^{13}C values, Bird *et al*. (1994) found altitude to be a significant influence on the δ^{13}C value of SOC, and Bol *et al*. (1999) and Huang *et al*. (1996) reported on effects of soil type specific processes on SOC δ^{13}C values. Thus, an approach was required that eliminates the factors which influence SOC δ^{13}C values other than actual vegetation change. Here, we report on the development and application of an isotopic-based index to assess vegetation changes over decadal (tens of years) timescales. This index was first tested at sites that had been studied in detail (core sites) with regard to vegetation change history and stable (δ^{13}C) and radiogenic (^{14}C) isotopic changes in size-separated and non-size separated (whole) SOC. The index is based on net isotopic difference between the size-separated fractions (individual carbon pools) and whole SOC. As such, it can be used to indicate whether the vegetation in an area has remained relatively stable, has thickened (increased proportion of woody biomass) or thinned (decreased proportion of woody biomass) over decadal timescales.

In the paper, we present an easy-to-use index that can be utilized in large field studies and requires only a limited set of soil analyses. Subsequently, the index was used to assess vegetation change at 44 sites distributed across the Burdekin catchment, northeastern Australia.

Materials and methods

Detailed SOC isotopic studies at core sites

Detailed SOC isotopic data from three core sites (collected in previous studies) were used to guide sampling strategies and to assist in devising suitable indices to describe vegetation change across contrasting woodland sites. Of these sites (Table 1; Fig. 1), Blue Range and Glen Innes are located within the Burdekin catchment, while Strathdarr is located in central Queensland to the west of the Burdekin catchment. Data described herein for Strathdarr, Blue Range and Glen Innes have been reported respectively in Krull & Bray (2005), Krull *et al*. (2005) and Bray *et al*. (2006). These sites, which differed in terms of soil type, climate and vegetation type (Table 1), were chosen in order to prevent a bias towards regional characteristics, and because information existed regarding recent vegetation change that could be used to assist interpretation of isotopic data

Table 1 Description of the detailed sites, used for calibration of the isotopic index I_{dec}

Site	Soil type	Climate		Major plant species	
		Average annual min., max. temperature (°C)	Average annual rainfall, potential evapotranspiration (mm/year)	Trees	Grasses
Strathdarr 23°13′S 143°57′E	Brown Vertosol	15.6°, 31.3°	447.2, 2908	*Acacia cambagei*	*Astrebla pectinata*
Blue range 19°09′S 145°24′E	Brown Chromosol	17.3°, 29.3°	661, 1737	*Eucalyptus crebra*	*Urochloa mosambicensis*
Glen Innes 23°27′S 146°22′E	Yellow Sodosol	14.8°, 29.4°	536, 1546	*Eucalyptus melanophloia*	*Triodia pungens*

(e.g. anecdotal information from landowner, aerial photography). All sites were paired sites, [i.e. they consisted of two plots in close proximity – one with apparent evidence of thickening (‘Tree’ site) and the other where vegetation change was not readily apparent and relatively stable conditions could be inferred (‘Open’ site)].

Analytical data collected at each site included δ^{13}C analyses of whole and size-separated SOC at eight depth intervals (0–2, 0–5, 5–10, 10–20, 20–30, 30–50, 50–70 and 70–100 cm) for individual soil cores and of litter and plant material. SOC was size separated into 200–2000 μm, 53–200 μm and <53 μm fractions. The combined 200–2000 μm and 53–200 μm fractions are referred to as the particulate organic carbon (POC) pool. The current vegetation status was described (plant species and their relative proportion, tree basal area, tree size class distribution, foliage projected cover, ground cover and stand biomass estimate). The tree size class distribution at the Glen Innes sites was assessed using ‘TRAPS’ methodology (Burrows *et al*., 2000, 2002). The basal circumference of all woody plants was measured at 30 cm height within five belt transects, which were 4 m wide, 25 m apart and 100 or 150 m long for the ‘Tree’ and ‘Open’ sites. Details of the site sampling strategy, sample processing, analyses and interpretation can be found in Krull & Bray (2005), Krull *et al*. (2005) and Bray *et al*. (2006). At the Strathdarr site all SOC size fractions and whole SOC samples from both the thickened and original grassland site were analysed for ^{14}C (Table 2).

Sampling and analyses for the regional Burdekin catchment study

The majority of the Burdekin catchment is situated in the semi-arid tropics of northeastern Australia. The study area within the Burdekin catchment includes all remnant (not cleared) vegetation that could be classified into three broad vegetation groups: silver-leaved ironbark (*Eucalyptus melanophloia* dominated woodland and similar communities), narrow-leaved ironbark (*Eucalyptus crebra* dominated woodland and similar communities), and woodlands on clay (*Eucalyptus* and *Acacia* woodlands associated with clay soils) based on regional ecosystem mapping (Sattler & Williams, 1999). Sites were selected using stratified random sampling within a geographical information system (GIS) analysis. The 44 sampled sites (Fig. 1) were assessed as being representative of the study area, based on available GIS data sets for vegetation type, rainfall and temperature in the wettest quarter (December–February), soil type and tree basal area (Bray *et al*., 2006). At each site, 25 soil cores from a 1 ha area (25 m × 25 m grid) were sampled and

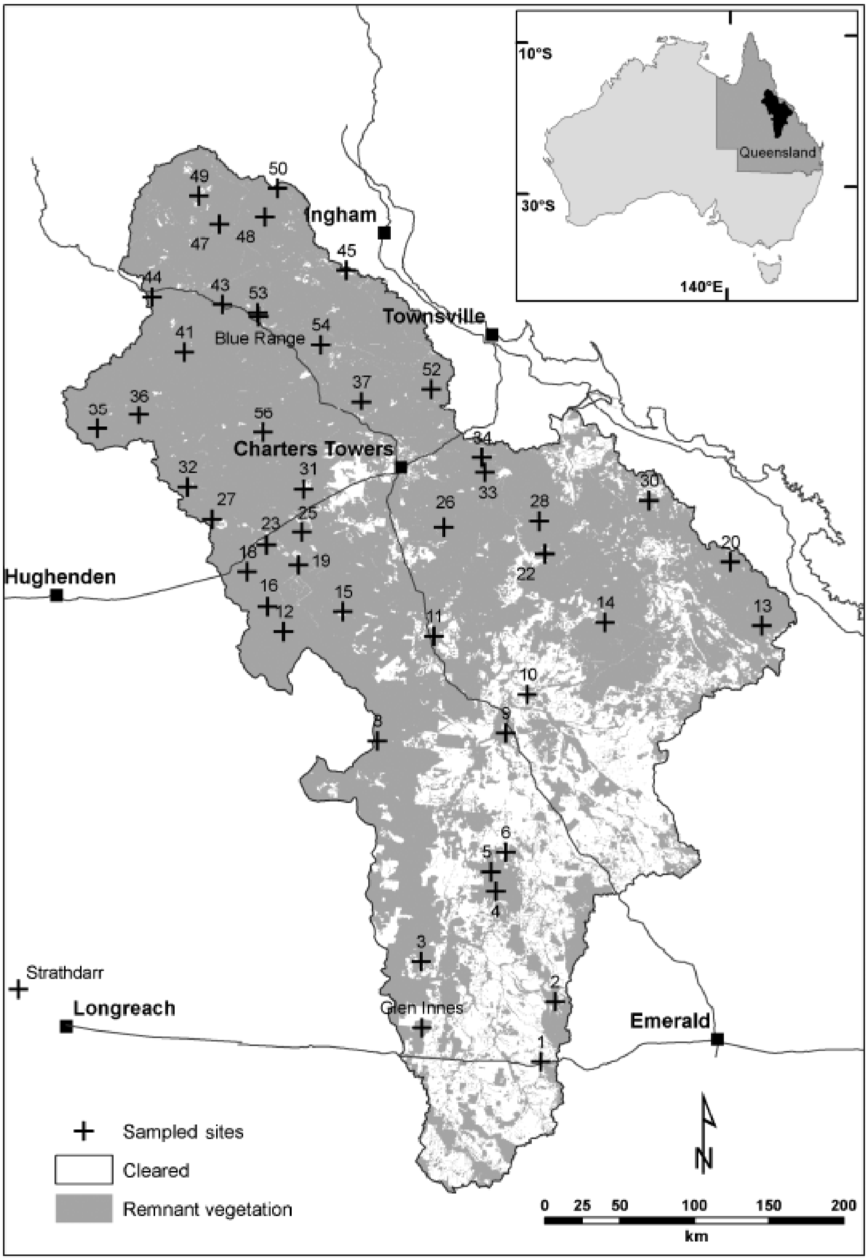


Fig. 1 Map of the Burdekin catchment with sample sites.

divided into the same eight depth intervals as for the core sites. While the cored soil samples from the three core sites were analysed individually to assess the degree of variability and error range in these ecosystems, core samples from the Burdekin catchment study were bulked to yield one composite sample per site for each soil depth increment. Soil samples were separated into the same size classes as for the core sites and analysed for δ^{13}C. Error from duplicate analysis was 0.3‰ for whole SOC and vegetation and 0.6‰ for POC fractions. Isotope results are reported in the conventional δ notation as per mil (‰) relative to the carbon isotopic ratio of the PDB standard (Peterson & Fry, 1987). AMS ^{14}C analyses of bulk soil and size fractions were carried out at the Rafter Radiocarbon Laboratory in Lower Hutt, New Zealand and at the Australian Nuclear Science and Technology Organisation (ANSTO). Radiocarbon results are reported in absolute per cent modern (pMC) relative to the NBS oxalic acid standard (HoxI) and corrected for decay since 1950 (Stuiver & Polach, 1977). Mean residence times (MRT) of soil organic matter with $>100\%$ modern carbon were estimated using a simple proportional replacement soil carbon model (Harkness *et al.*, 1991). Details on sample preparation and analyses can be found in Krull & Bray (2005) and Krull *et al.* (2005).

Results and discussion

SOC analyses at the core sites

At the three core tree sites, δ^{13}C data of the size-separated POC fraction in the surface and subsurface soil (to 30 cm depth) confirmed evidence from landowners and aerial photography of a definite increase in woody (C_3) biomass (reported previously in Krull *et al.*, 2005; Krull & Bray, 2005; Bray *et al.*, 2006). The δ^{13}C data of the whole soil and <53 μm size separated fraction reflected recent vegetation change only in the surface soil horizon. The δ^{13}C of deeper soil horizons indicated a previously more open (greater proportion of C_4 grasses) vegetation status. As a result, for sites that had experienced recent woodland thickening, there was an increasing difference between the δ^{13}C POC and the bulk (or <53 μm) SOC with depth. In the core sites where direct evidence suggested that the vegetation status had remained reasonably stable ('Open' sites), there was not a significant difference in δ^{13}C value between the size fractions, and the difference in δ^{13}C values between surface and subsurface horizons in the whole soil and <53 μm fraction was less than at the 'Tree' sites.

Thus, we observed firstly that at sites where anecdotal evidence suggested thickening ('Tree' sites), there was an increased deviation with depth in δ^{13}C values between the POC (affected by recent C_3 input) and both the whole SOC and the <53 μm fraction. Secondly, the difference in δ^{13}C values between surface and subsurface soil was consistently greater at the 'Tree' site compared with the 'Open' sites. Similar findings have been observed in other studies employing δ^{13}C analyses of whole and size-separated SOC to investigate timing and extent of vegetation thickening (e.g. Connin *et al.*, 1997; Boutton *et al.*, 1998, 1999).

Previously published data on the MRT of labile and stable SOC fractions (e.g. Cambardella & Elliott, 1992; Balesdent, 1996; Balesdent & Mariotti, 1996; Trumbore & Zheng, 1996; Baisden *et al.*, 2002a, b) and our own ^{14}C analyses and calculated MRTs (Table 2) confirm that even in subsurface soil horizons, down to 90 cm in the study by Connin *et al.* (1997), the POC fraction is 'modern', i.e. was formed after the nuclear bomb experiments in the 1950s and accordingly has MRTs of decadal scales. Hsieh (1992) found that the active SOC pool of agricultural soils in the United States may vary from 34 to 67 years, which is similar to the estimated MRT of 72 years of the active SOC pool reported by Jenkinson & Rayner (1977) for Rothamsted. Our ^{14}C

Table 2 Conventional ^{14}C ages [as defined by Stuiver & Polach (1977)] and mean residence time (MRT) of soil organic carbon fractions at the 'Open' and 'Tree' sites at Strathdarr

'Open' site	Bulk		200–2000 μm		53–200 μm		<53 μm	
Depth (cm)	^{14}C age	MRT	^{14}C age	MRT	^{14}C age	MRT	^{14}C age	MRT
0–2	Modern	178	Modern	6.5	Modern	9.4	Modern	227
0–5	158		Modern	70	Modern	54	314	
5–10	296		Modern	60	Modern	58	189	
10–20	722		Modern	80	Modern	61	894	
20–30	868		Modern	84	Modern	82	810	
30–50	1113							
50–70	1965							
70–90	3734							
'Tree' site								
0–2	Modern	12.4	Modern	6.9	Modern	7.8	Modern	20
0–5	164		Modern	37	Modern	73	274	
5–10	1392		Modern	61	Modern	79	1884	
10–20	382		Modern	55	Modern	94	675	
20–30	525		703		Modern	182	655	
30–50	2891							
50–70	4253							
70–90	5450							

'Modern' denotes soil organic carbon formed since 1950 for which MRTs were calculated based on a proportional replacement model Harkness *et al.* (1991).

data from the Strathdarr site show similar estimates for the MRT of the modern 0–30 cm POC fraction (excluding the 0–2 cm interval) with the 'Open' site having slightly lower average MRTs (69 years) than the 'Tree' site (79 years) (Table 2). Thus, the δ^{13}C values of the POC fraction reflect a SOC pool that consists largely of relatively young C with a decadal turnover time, much of it formed after the 1950s.

By comparison, a 'modern' carbon contribution in the whole SOC and the $<53\,\mu$m fraction, which corresponds to the stable humic pool (HUM) in the Roth-C model and the passive pool (SOM3C) in Century (MRT: 200–4000 years; http://www.nrel.colostate.edu/projects/century/) was only apparent in the top 2-cm-depth interval at the Strathdarr site (Table 2). Below this depth, there was no apparent contribution of carbon derived from the nuclear bomb experiments, and similar observations have been made by Trumbore *et al.* (1996), Boutton (1996), Trumbore (1997), Wang *et al.* (1999), Guillet *et al.* (2001), Gaudinski *et al.* (2000), Wang & Hsieh (2002) and Biedenbender *et al.* (2004). These data indicate that δ^{13}C of the whole soil and $<53\,\mu$m fractions at depth are representative of vegetation status and litter inputs that occurred sometime during the Holocene and, therefore, represent vegetation conditions over centennial and possibly millenial timescales. By comparison, surface soil samples (0–2 cm) included a significant proportion of C that was generated after the 1950s with a decadal turnover time. Our ^{14}C data and analyses from other studies (e.g. Connin *et al.*, 1997; Boutton *et al.*, 1999; Smith & Johnson, 2003; Biedenbender *et al.*, 2004; Desjardins *et al.*, 2004; Henderson *et al.*, 2004), confirm that δ^{13}C of size fractions and comparison of different depth intervals of whole SOC could be used to assess vegetation changes that occurred over decadal vs. centennial and millennial timescales.

Derivation of the decadal index

To devise an index that illustrates decadal vegetation change (I_{dec}), we utilized the δ^{13}C data of the POC fraction (53–2000 μm) and the whole SOC. For the core sites, all fractions (200–2000, 53–200 and $<53\,\mu$m) and whole SOC were analysed for δ^{13}C at all depth intervals and the proportion of each fraction was calculated. From this information, we were able to assess whether simplification of required data was possible without compromising resolution and reliability. The δ^{13}C data of the 53–200 μm fraction were generally less variable than the 200–2000 μm fraction. However, both fractions varied around similar values; therefore, we chose to utilize the combined POC (53–2000 μm) fraction for the calculation of I_{dec} to simplify the approach. The δ^{13}C data of the $<53\,\mu$m fraction were very similar to the whole SOC data, because mineral soils (soil below 5 cm) consist predominately (80% or more) of the $<53\,\mu$m fraction (e.g. Feller & Beare, 1997; Feller *et al.*, 2000; Krull *et al.*, 2005). Thus, to simplify analyses, we utilized the δ^{13}C of the whole SOC to represent mostly the humified SOC associated with the 'stable' or 'passive' carbon pool. However, Wynn *et al.* (2005) reported that in some sandy soils the proportion of the $>53\,\mu$m fraction can be significantly higher. Thus, it is important that size fraction data of the whole soil profile be checked for trends that show an unusually high proportion of carbon in the POC fraction.

While several studies have reported 'modern' ^{14}C ages of the POC fraction to a depth of 100 cm, we decided on a more conservative approach and to limit use of the POC data to a depth of 50 cm, because in many soils the carbon content of the POC fraction tends to become very low at depths below 50 cm, which would result in greater uncertainty in using these data. Thus, the required data to calculate I_{dec} are δ^{13}C of whole SOC and the POC fraction by depth interval (0–5, 5–10, 10–20, 20–30 and 30–50 cm). To determine I_{dec}, the δ^{13}C of the whole SOC is subtracted for each depth interval from the δ^{13}C of the POC (2000–53 μm) fraction for that interval. Differences are expected to occur between the individual depth intervals in the POC fraction. This is due to short-term fluctuations in vegetation status resulting from drought or fire and differential inputs of litter and dead root material at different depths. Because I_{dec} aims to give precision about vegetation changes that occurred over decadal time scales and not to be of greater temporal (annual) sensitivity, the average of the subtractions in the 0–50 cm interval is used to calculate I_{dec},

$$I_{\mathrm{dec}} = \sum\left(\delta^{13}\mathrm{C}_{\mathrm{whole},n} - \delta^{13}\mathrm{C}_{\mathrm{POC},n}\right)/\mathrm{N}, \tag{1}$$

where subscripts denote the type of material ('whole' or 'POC') and '*n*' the respective depth interval (e.g. 2.5, 7.5, 15 cm) of the soil layer for a total number of 'N' (e.g. 5) intervals.

To ascertain the range of values delineating stable conditions (i.e. no vegetation change), we reviewed published data describing the range in δ^{13}C data between POC fractions and whole SOC that occur independent of vegetation change. For example, it is commonly observed that the most labile (larger) fractions have the most depleted (least decomposed) values while more ^{13}C-enriched values are reported with decreasing particle size (increased degree of humification) (e.g. Balesdent, 1996; Balesdent & Mariotti, 1996; Boutton, 1996). Thus, isotopic differences among size fractions are to a certain degree expected and are related to soil decomposition processes and not due to vegetation change. Most studies investigating variability of δ^{13}C of size fractions from soils that had not experienced vegetation change found that the differences were commonly between 0.1 and 1.6‰ and always less than 1.9‰ (e.g. Balesdent & Mariotti, 1996; Accoe *et al.*, 2002; Bird *et al.*, 2002; Smith & Johnson, 2003; Krull *et al.*, 2005; Wynn *et al.*, 2005). Thus, we adopted a conservative approach and chose the range between 0 and 1.9‰ to indicate stable conditions, values >1.9‰ to indicate decadal thickening and negative values to indicate thinning (Fig. 2).

Application of I_{dec} *to core sites*

Applying I_{dec} to the core sites yielded results that corresponded with information from landowners and aerial photographs with regard to vegetation status (summarized in Table 3).

At Strathdarr, for the site identified as having recently thickened ('Tree' site), I_{dec} was 4.5, indicating recent thickening (as confirmed by the landowner) with the current vegetation state containing a higher proportion of woody plants than the vegetation during the previous centuries. The value for I_{dec} at the corresponding non-thickened grassland ('Open' site) site was 1.1, denoting relatively stable conditions in the decadal past and possibly also over longer (centennial) timescales (Krull *et al.*, 2005). Long-term stability of grasslands in Australia has been attributed to regular fire intervals both from natural fires, as well as due to traditional Aboriginal fire-stick farming (Yibarbuk *et al.*, 2001; Bowman *et al.*, 2004).

At Blue Range, the record of recent thickening (landowner and aerial photography; Krull & Bray, 2005) has been confirmed for the 'Tree' site with an I_{dec} of 2.8, compared with an I_{dec} of 0.3 for the corresponding 'Open' site, which indicates stable conditions in the decadal past.

There was no documented history for the Glen Innes site, however; it was chosen because there was a difference in the tree size class distribution between the two plots (Fig. 3). Based on the results of the current tree size class distribution, it was hypothesized that the 'Tree' site may have recently thickened due to a relatively higher proportion of small trees compared with the nearby (within 1.4 km) 'Open' site which had a higher proportion of larger trees. The 'Tree' site also had a

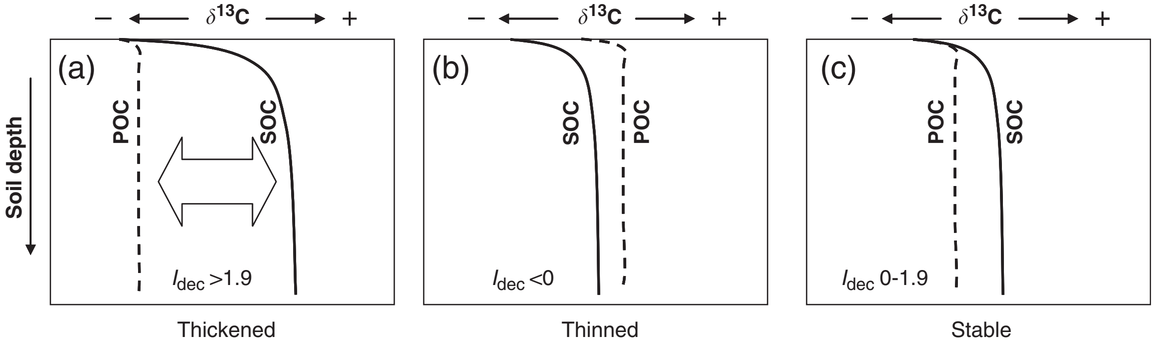


Fig. 2 Schematic representation of isotopic profiles that are characteristic of I_{dec}, indicating 'thickened' (a) 'thinned' (b) and 'stable' (c) conditions. Particulate organic carbon (POC) δ^{13}C are represented by data from the combined >200 and 53–200 μm fractions and soil organic carbon (SOC) δ^{13}C are the organic carbon data of the whole soil.

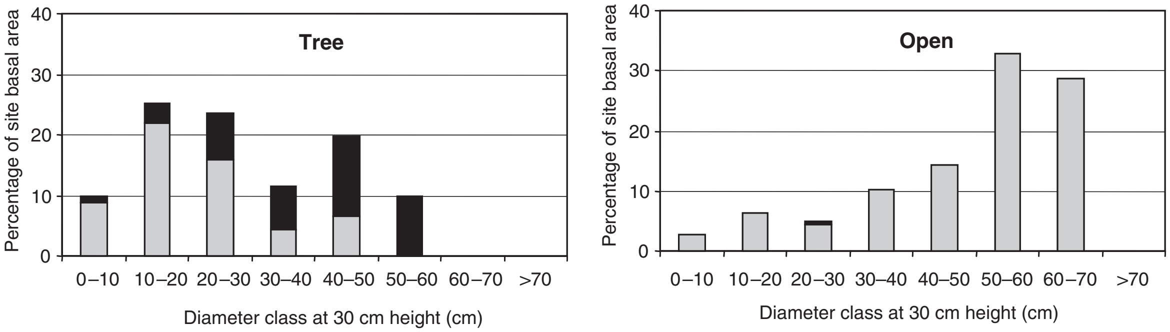


Fig. 3 Size class distribution of trees for the 'Tree' and 'Open' plots at the Glen Innes site, based on basal area assessments. Grey bars indicate live trees and shrubs and black bars indicate standing dead trees. The live basal area was 6.7 and 10.9 $\mathrm{m}^2\,\mathrm{ha}^{-1}$ (at 1.3 m height) for the 'Open' and 'Tree' sites, respectively.

doi: 10.1111/j.1365-2486.2007.01376.x

Table 3 Summary of supporting evidence for vegetation change and calculated I_{dec} for each of the core sites

Site	Description		I_{dec}
Strathdarr*	Tree site	Landowner believed that the trees had increased over the last 50 years. Aerial photography resolution was not sufficient to determine tree cover change; however some trees were present in the 1950s	4.5
	Open site	Landowner believed the grassland had remained open over the last 50 years. Aerial photography indicated the site was grassland in the 1950s	1.1
Blue Range†	Tree site	Landholder believed the trees had increased over the last 50 years. Aerial photography analysis indicated the tree cover had increased since the 1950s	2.8
	Open site	Landholder believed the site had remained open or that tree cover had decreased slightly over the last 50 years due to tree death associated with droughts in the 1980s and early 1990s Aerial photography analysis indicated the site had thinned since the 1950s	0.3
Glen Innes‡	Tree site	A high proportion of the tree basal area was present as small trees indicating the site may have recently thickened, although some dead trees were present (Fig. 3). Aerial photography analysis indicated that the shrub/small tree cover had increased since the 1950s (Table 4)	1.4
	Open site	Site was an open 'mature' woodland dominated by large trees (Fig. 3). Aerial photography analysis indicated the site had remained stable since the 1950s (Table 4)	0.1

*Krull *et al.* (2005), †Krull & Bray (2005), ‡Bray *et al.* (2006).

greater number of dead trees (Fig. 3) compared with the 'Open' site, which was attributed to the severe drought in the early 1990s. Furthermore, the 'Open' site had a lower live tree basal area ($6.7\,\mathrm{m^2\,ha^{-1}}$ at 1.3 m height) compared with the 'Tree' site ($10.9\,\mathrm{m^2\,ha^{-1}}$). Table 4 shows the results of an assessment of woody vegetation cover from aerial photography between 1952 and 2002 over a 25 ha area, which included the 1 ha sampled area, using the technique of Fensham *et al.* (2003). The results from this assessment showed that the 'Open' and 'Tree' site had a similar woody plant cover (trees and shrubs) in the 1950s, but that in 2002, the shrub (small tree) cover in the 'Tree' site had increased.

These data together with the large number of dead trees suggest that the 'Tree' site had undergone thickening and thinning changes over a relatively short period of time (less than 50 years) compared with the apparently more stable 'Open' site. Isotopic analyses showed differences between the two sites, resulting in values for I_{dec} of 1.4 for the 'Tree' and 0.1 for the 'Open' site. However, the higher value for the 'Tree' site is below the critical threshold value to support the occurrence of thickening, using our index. Thus, in the case of the Glen Innes 'Tree' site, alternating thickening and thinning cycles might have occurred (based on the aerial photography, tree size class distribution data and the slightly greater I_{dec} of the 'Tree' compared with the 'Open' site); however, these fluctuations were too short-lived and cyclical to be detected by I_{dec} as it identifies longer-term vegetation changes that affect the decadal turnover time of the POC fraction. In the case of short-lived (annual) cycles (e.g. droughts), where thickening and thinning phases rapidly alternate, a relatively stable state for decadal timescales will be documented by I_{dec}.

Table 4 Woody plant (tree and shrub) cover at Glen Innes assessed from aerial photography using the technique of Fensham *et al.* (2003)

	Tree cover (%)	Shrub cover (%)	Total woody plant cover (%)
'Open' site			
1952	37.5	9.5	47.0
2002	36.5	10.0	46.5
% change (2002/1952)	−1.0	+ 0.5	−0.5
'Tree' site			
1952	40.0	6.5	46.5
2002	39.5	18.0	57.5
% change (2002/1952)	−0.5	+ 11.5	+ 11

Aerial photography analysis conducted by Fairfax (unpublished data) covered a 25 ha area which included the 1 ha sites.

Results from these core sites (summarized in Table 3) confirmed the utility of I_{dec} to detect vegetation changes that have occurred over decadal timescales. Because I_{dec} is operationally defined by the turnover time of the POC fraction, it applies to periods of the same order as the MRTs of the relevant fraction. Thus, the resolution of the index may vary according to the turnover time of the fraction. Accordingly, application of the index to a new area would require some knowledge of the average MRTs of the POC fraction, as was acquired here at the core sites.

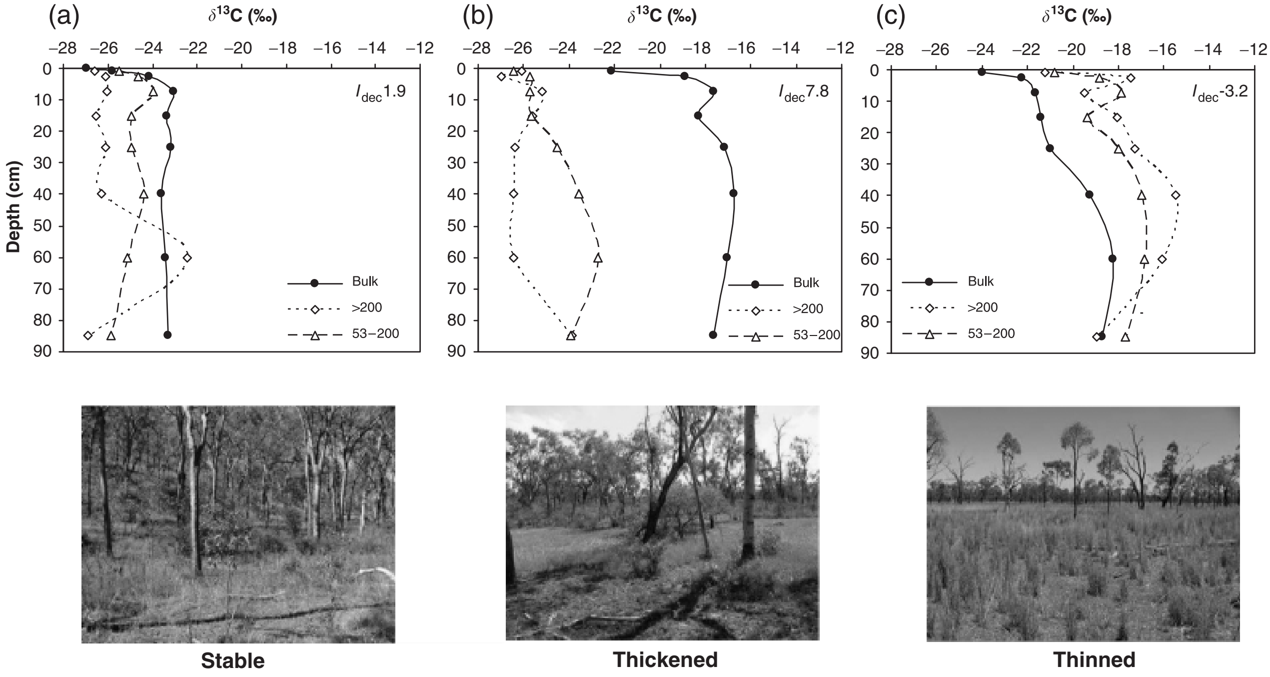


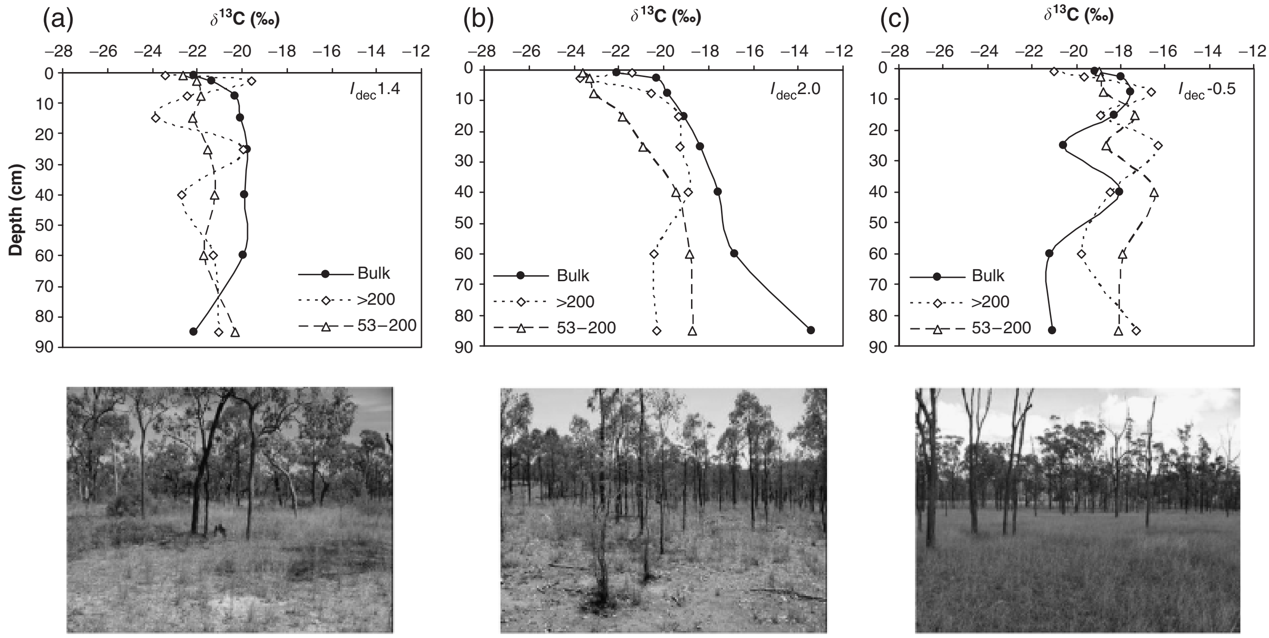
Fig. 4 Examples of sites from the Burdekin catchment, displaying ‘classical’ trends for (a) ‘stable’ (GA13), (b) ‘thickened’ (GA33) and (c) ‘thinned’ (GA56) vegetation change.

The aim of this paper is to develop an index that can be applied not just in the region where it was developed but elsewhere in the world where grasses are mostly C_4 (i.e. clear isotopic distinction between trees and grasses). By developing the index using three core sites that differed in climate, soil and vegetation type we expect the index to have widespread applicability. In order to assess whether the results from Australian ecosystems were applicable elsewhere in the world, we chose to apply them to the studies by Boutton *et al.* (1998, 1999) on a savanna ecosystem as they also employed size separation methods and ^{14}C dating. Their results suggested recent (decadal) thickening of woodlands and groves in the study area; therefore one would expect an I_{dec} of >1.9 if our index were valid in sites outside Australia. Application of the index to Boutton *et al.*’s (1998, 1999) data yielded results of 3.0 for the grove, 3.9 for the transition woodland and 6.0 for the drainage woodland, all indicating decadal thickening. These results are in agreement with Boutton *et al.*’s interpretation, noting that the drainage woodland had the strongest C_4 component (least tree coverage) in the past and thus showed the greatest degree of thickening.

$\delta^{13}C$ and I_{dec} examples from the Burdekin catchment study sites

I_{dec} values indicated that 64% of the 44 study sites in the Burdekin catchment had thickened, 29% were stable and 7% had thinned. These results imply a regional vegetation thickening trend over decadal timescales (last 50–100 years) which is supported by an analysis of uncleared woodland using aerial photography between 1951 and 1995 in central Queensland and a more recent analysis of eucalypt woodlands using ground based monitoring over the last two decades (Burrows *et al.*, 2002; Fensham *et al.*, 2003). Thickening over this time period has been attributed to a combination of land management changes (fire suppression, cattle grazing) and CO_2 fertilization due to rising CO_2 concentrations in the atmosphere over the last 100 years (Gifford & Howden, 2001; Henry *et al.*, 2002; Sharp & Whittaker, 2003; Berry & Roderick, 2006).

Figures 4 and 5 show the $\delta^{13}C$ profiles and I_{dec} from selected study sites in the Burdekin catchment that illustrate stable, thickened and thinned situations. Figure 4 shows isotopic data that illustrate decadal trends that can be regarded as ‘classical’ trends. Trends that can be viewed as ‘classical’ stem from results of agricultural vegetation change studies where one monoculture (e.g. C_3 wheat) is instantly replaced by another (e.g. C_4 maize). In such cases (e.g. Balesdent *et al.*, 1987, 1988; Gleixner *et al.*, 1999; Wiesenberg *et al.*, 2004), spatial variability will be low and turnover time of SOC derived from the previous and the new crop can be accurately monitored by $\delta^{13}C$ analysis of SOC and its fractions. In such cases, the resultant data have low variability and clear trends that represent an obvious illustration of the vegetation change history.



Stable Thickened Thinned

Fig. 5 Examples of sites from the Burdekin catchment, displaying common trends for (a) 'stable' (GA19), (b) 'thickened' (GA27) and (c) 'thinned' (GA30) vegetation change.

Figure 4a illustrates stable conditions over decadal timescales ($I_{\mathrm{dec}} = 1.9$) for site GA 13, located in the eastern part of the Burdekin catchment (Fig. 1, Table 4). The isotopic trends exemplify a site that maintained a relatively stable vegetation status over the last tens of years and possibly longer.

A classical isotopic trend for decadal thickening occurs at site GA 33 (Fig. 4b, Table 5). The large I_{dec} of 7.8 illustrates the considerable difference of δ^{13}C between the whole SOC and the POC fractions. The POC fractions vary around a similar mean in the top 30 cm and correspond well with the δ^{13}C of the litter layer (−26.0‰), confirming that the POC fraction reflects the recent vegetation composition. A trend from a greater to a lesser proportion of trees ('thinning') over the last few decades is evident at GA 56, illustrated by a negative I_{dec} (−3.2) (Fig. 4c). The δ^{13}C of the POC fractions are consistently more ^{13}C-enriched than the whole SOC δ^{13}C values and both fractions ($>$200 and 53–200 μm) vary around similar values.

However, such 'classical' trends as shown in Fig. 4 tend to be uncommon in woody grasslands, which are heterogeneous in terms of spatial distribution of plant species. Furthermore, in natural ecosystems vegetation change tends to proceed gradually or in irregular episodic events over years rather than instantly as in agricultural systems.

Figure 5 illustrates isotopic trends for 'stable', 'thickened' and 'thinned' conditions that illustrate the variable nature of savanna woodlands. Figure 5a shows isotopic data for site GA 19 (Fig. 1, Table 5) for which I_{dec} (1.4) indicates stable conditions. However, compared with the 'classical' stable site GA 13 (Fig. 4a), isotopic variability is much greater (up to 4.3‰ in the >200 μm fraction). In fact, for most sites of our study, the 53–200 μm fraction showed a greater consistency within the soil profile than the >200 μm fraction. This is most likely due to a greater variety of organic carbon sources contributing to the >200 μm fraction, which can include decomposing litter, root material (e.g. Bird *et al.*, 2003), charcoal (Skjemstad *et al.*, 1990; Krull & Skjemstad, 2003) and ancient carbon from geological sources (e.g. Rethemeyer *et al.*, 2004).

I_{dec} for site GA 27 (Fig. 1, Table 5) indicates decadal thickening ($I_{\mathrm{dec}} = 2.0$) (Fig. 5b). Similar to GA 19, the >200 μm fraction displays greater variability than the 53–200 μm fraction; however, in this case the variation is more systematic in that much of the uppermost 40 cm is characterized by a significantly ^{13}C-enriched >200 μm fraction with values close to those of the whole SOC. In addition, the 53–200 μm fraction shows systematic ^{13}C enrichment with depth. Thus, at this site, there is not only a significant isotopic difference between the whole SOC and POC fractions but between the individual POC fractions as well. While the character of the isotopic differences between the individual POC fractions is not factored in the determination of I_{dec} (as the average δ^{13}C value is used), it can be important

Table 5 Description of the sites from the Burdekin catchment region (Fig. 1) study that are discussed as examples of applying the I_{dec} index (Figs 4 and 5)

		Soil type	Climate		Major plant species	
Site	I_{dec}		Average annual min, max temperature (°C)	Average annual rainfall, potential evaptranspiration (mm/year)	Trees	Grasses
GA 13 21°02′ S148°26′E	1.9	Brown-Orthic Tenosol.	15.6, 25.9	1269, 1725	*Corymbia clarksoniana*	*Bothriochloa decipiens*
GA 33 20°06′ S146°46′E	7.8	Black Chromosol	16.3, 28.6	739, 1721	*Eucalyptus brownii*	*Bothriochloa pertusa*
GA 56 19°52′ S145°26′E	−3.2	Red Ferrosol	16.7, 29.5	673, 1655	*Eucalyptus crebra*	*Bothriochloa ewartiana*
GA 19 20°40′ S145°39′E	1.4	Brown Chromosol	16.8, 30.6	645, 1612	*Eucalyptus melanophloia*	*Aristida* spp.
GA 27 20°23′ S145°08′E	2.0	Red Chromosol	15.7, 28.9	676, 1610	*Eucalyptus quadricostata*	*Bothriochloa erwartiana*
GA 30 20°17′ S147°45′E	−0.5	Yellow Chromosol	16.5, 27.8	897, 1794	*Eucalyptus crebra*	*Bothriochloa pertusa*

information in determining fluctuations in vegetation status over the last few decades. This has been documented, for example, in a study by Krull & Bray (2005), which showed that the effect of recent severe droughts, associated with widespread tree death, can be expressed in the isotopic record. Thus, the fact that the δ^{13}C of the $>200\,\mu$m fraction in the uppermost 40 cm is almost as ^{13}C enriched as the whole SOC, whereas the 53–200 μm fraction displays the most ^{13}C-depleted values in this interval, suggests that thickening had most likely not been a consistent process. In fact, the presence of dead trees at site GA 27 (35% of the site basal area), which were suspected to have died during the severe drought in this area in the early 1990s, as well as the presence of many young trees (66% of the live basal area), supports the interpretation of a thickening of the tree cover followed by a reduction of tree cover due to drought and then recent tree cover recovery and thickening (Fig. 5b).

Site GA 30 (Fig. 1, Table 5) has been classified as recently thinned ($I_{\mathrm{dec}} = -0.5$; Fig. 5c). However, compared with the 'classical' trend of site GA 56 (Fig. 4c), where thinning had only occurred recently and probably can be largely attributed to the severe drought in the last few decades, at GA 30 all of the fractions, as well as the bulk soil seem to indicate thinning. While the previous examples have shown that the POC fraction, particularly the $>200\,\mu$m fraction, can often fluctuate within the soil profile, at GA 30 the whole SOC displays a similarly variable trend. The oscillating pattern is related to the unusually high level of POC (67%) in the SOC, resulting in a greater influence of that fraction on the whole SOC. The influence of the 53–200 μm fraction on the whole SOC can be inferred by the covariation in isotopic values, especially in the 10–40 cm soil depth range. In this case, the decadal thinning at GA 30, which resulted in over 60% dead basal area, can most likely be attributed to droughts in the mid 1980s and 1990s.

Conclusion

An index (I_{dec}) was developed, utilizing the distinct isotopic difference between trees (C_3) and tropical grasses (C_4) and the δ^{13}C record in SOC size fractions and the whole SOC, to provide a generic method to assess vegetation change over decadal timescales. The index normalizes individual site-specific isotopic data and allows interpretation of vegetation change over a large area regardless of local site characteristics such as climate, vegetation or soil type. The index enables broad-scale (regional) assessment of historical vegetation change patterns. Such an assessment has not been possible in the past and the isotopic approach identified here can guide modelling of future climate- or management-related vegetation dynamics in subtropical and tropical areas where the majority of grasses use the C_4 photosynthetic pathway. In addition, the data necessary to determine I_{dec} can be utilized for more detailed evaluation of decadal vegetation changes, especially extreme effects such as fire or drought that can cause short-term fluctuations within a longer-term vegetation change trend. Analyses of the 44 sites in the Burdekin catchment indicated decadal thickening at 64% of sites. This indicates that large-scale landscape changes have occurred in the Burdekin catchment region, which will on the one hand lead to an increase in carbon storage in woody biomass but may also adversely affect landholders by diminishing the grass resource. Sensible management practices are necessary to ensure a productive and sustainable land resources without compromising the natural ecosystems.

Acknowledgements

The authors gratefully acknowledge the financial and in-kind assistance provided by the CRC for Greenhouse Accounting, Queensland Natural Resources and Water, Queensland Department of Primary Industries and Fisheries and CSIRO Land and Water. An AINSE grant from ANSTO to Professor Farquhar (grant 05/052P) provided resources for AMS analyses of the grassland soil. Russell Fairfax is thanked for the aerial photography analysis at the Glen Innes site. We thank Matt Forbes and Sandrina Alves for their diligent work in the laboratory and Lex Cogle, Dale Heiner, Michael Yee, Mal Rutherford, Nev Christianos, Mark Keating and John Compton for their much appreciated help in the field and sample processing. Discussions with John Raison, Bill Burrows, Kelvin Montagu, Jeff Baldock and Jan Skjemstad helped to improve the design of the study and the manuscript.

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