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How widespread is woody plant encroachment in temperate Australia? Changes in woody vegetation cover in lowland woodland and coastal ecosystems in Victoria from 1989 to 2005

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Running head: Woody plant encroachment in temperate Australia

ABSTRACT

Aim Encroachment or densification by woody plants affects natural ecosystems around the world. Many studies have reported encroachment in temperate Australia, particularly in coastal ecosystems and grassy woodlands. However, the degree to which published studies reflect broad-scale changes is unknown because most studies intentionally sampled areas with conspicuous densification. We aimed to estimate changes in woody vegetation cover within lowland grassy woodland and coastal ecosystems in Victoria from 1989 to 2005 to determine whether published reports of recent encroachment are representative of broad-scale ecosystem changes.

Location All lowland grassy woodland and coastal ecosystems (ca. 6.11 x 10^5 ha) in Victoria, Australia. Four major ecosystems were analysed: Plains woodland, Herb-rich woodland, Riverine woodland and Coastal vegetation.

Methods Changes in woody vegetation cover from 1989 to 2005 were assessed based on state-wide vegetation maps and Landsat analyses of woody vegetation cover conducted by the Australian Greenhouse Office's National Carbon Accounting System. The results show changes in woody cover *within* mapped patches of native vegetation, rather than changes in the extent of woody vegetation resulting from clearing and revegetation.

Results When pooled across all ecosystems, woody vegetation increased by 18,730 ha from 1989 to 2005. Woody cover within Riverine woodlands and Plains woodlands each increased by > 7000 ha. At the patch scale, the mean percentage cover of woody vegetation in each polygon increased by > 5% in all four ecosystems: Riverine woodlands (+9.2% on average), Herb-rich woodlands (+7.6%), Plains woodlands (+6.7%) and Coastal vegetation (+5.9%). Regression models relating degree of encroachment to geographic and climatic variables were extremely weak ($r^2 \leq 0.026$), indicating that most variation occurred at local scales rather than across broad geographic gradients.

Main conclusions At the scale of observation, woody vegetation cover increased in all lowland woodland and coastal ecosystems over the 16-year period. Thus, published examples of encroachment in selected coastal and woodland patches do appear to reflect widespread increases in woody vegetation cover in these ecosystems. This densification appears to be associated with changes in land management rather than post-fire vegetation recovery and is likely to be ongoing and long-lasting, with substantial implications for biodiversity conservation and ecosystem services.

Keywords

Australia, densification, ecosystem dynamics, long-term vegetation change, remote sensing analysis, vegetation thickening, woody weed invasion, woody plant encroachment. .

INTRODUCTION

Structural changes to natural ecosystems caused by encroachment of dominant woody plants affect ecosystem processes and services, biodiversity patterns, and economic utilisation of natural ecosystems around the globe (Scholes & Archer, 1997; Briggs *et al.*, 2005; Cramer *et al.*, 2008). Woody plant encroachment (variously called 'woody weed' or scrub thickening, invasion, densification and expansion) has received most attention in semi-arid and sub-tropical rangelands where increases in woody vegetation, and associated declines in herbaceous fodder plants, can have major economic impacts on rangeland grazing enterprises (Scholes & Archer, 1997; Van Auken, 2000; Asner *et al.*, 2004).

Encroachment is commonly triggered by reductions in fire frequency and intensity following consumption of herbaceous plants (fuel) by grazing livestock. However, other factors can also promote encroachment, including reduced grazing intensity, above-average rainfall and increasing atmospheric CO_2 (Scholes & Archer, 1997; Bond & Midgley, 2000; Briggs *et al.*, 2005; Fensham *et al*., 2005; Banfai & Bowman, 2006). In addition to rangeland regions, encroachment has also caused serious problems in more intensively developed temperate agricultural regions following agricultural abandonment (Cramer & Hobbs, 2007; Cramer *et al.*, 2008) and disruption of natural fire regimes by ecosystem fragmentation (Briggs *et al.*, 2005).

In Australia (as elsewhere in the world), encroachment has been intensively studied in semi-arid and sub-tropical rangelands (Noble, 1997; Burrows, 2002; Sharp & Whittaker, 2003; Fensham *et al.*, 2005; Lehmann *et al*., 2008). However, examples are increasingly being documented from a variety of fragmented ecosystems in temperate climate regions in southern Australia (Withers & Ashton, 1977; Bren, 1992; Bennett, 1994; Lunt, 1998a; Costello *et al.*, 2000; Parker & Lunt, 2000; Watson, 2005; Emeny *et al.*, 2006; Price & Morgan, 2006, 2009; Franco & Morgan, 2007; Gent & Morgan, 2007). In contrast to production-orientated rangeland studies, most studies from temperate Australia have focused on potential impacts of encroachment on biodiversity conservation and ecosystem processes, particularly in nationally threatened and highly fragmented ecosystems such as temperate grasslands and woodlands (e.g. Costello *et al.*, 2000; Watson, 2005; Franco & Morgan, 2007; Price & Morgan, 2009). For example, Costello *et al*. (2000) documented a linear decline in plant species richness with increasing age of shrub encroachment, with 76% of species being lost after 20 years.

Despite their prominence in the Australian contribution to the global literature on woody plant encroachment, nearly all such studies from south-eastern Australia share a singular deficiency. Most document changes in a single site, and site selection has usually been intentionally biased, since studies were conducted in order to describe unusually notable examples of densification. Consequently, it is not possible to assess whether the patterns, processes or impacts of encroachment that are documented in the published literature are representative of more widespread changes across broader ecosystems. This presents dilemmas for researchers and land managers. Researchers may be prone to infer that published patterns, mechanisms and impacts of encroachment are widespread and ecologically important over large areas; unfortunately, the selective sampling regimes adopted do not enable this conclusion to be met. By contrast, managers may be loathe to manage encroachment in particular sites in the absence of a broader spatial context, i.e. they need to know how widespread the problem is.

The small sample areas adopted in most encroachment studies from southern, temperate Australia reflect both the high degree of ecosystem fragmentation in the regions studied (and consequent small patch size), and the frequent use of aerial photograph interpretation, which is labour intensive. The average study area size in eight single-site studies was 1742 ha (range 144-6487 ha; Bren, 1992; Bennett, 1994; Lunt, 1998a; Costello *et al*., 2000; Parker & Lunt, 2000; Franco & Morgan, 2007; Gent & Morgan, 2007; Price & Morgan, 2009). Fortunately, the increasing duration of readily available satellite imagery means that remote sensing can now be used to document ecosystem changes across large areas over many decades. Landsat images are available from the early 1970s, and Landsat image analysis provides a feasible method to assess changes in woody vegetation cover across 2-3 decades over large areas, and a means of overcoming the potential site selection biases in the published record of vegetation encroachment from temperate regions of Australia.

Recently the Australian Greenhouse Office (AGO) completed a national assessment of changes in woody vegetation cover for the National Carbon Accounting System (NCAS), based on analysis of 14 successive Landsat images from 1972 to 2005. The analyses incorporated rigorous quality control procedures (AGO, 2002; Furby, 2002a, b; Furby & Woodgate, 2002; Lowell *et al.*, 2003), and results provide an accurate assessment of temporal changes in woody vegetation cover across all but arid Australia, at a 25 x 25 m pixel size. The AGO programme was designed to document changes in forest cover caused by broad-scale clearing and revegetation of native vegetation for use in national carbon accounting monitoring as required under the Kyoto protocol. Consequently, changes in woody cover within natural areas and conservation reserves were not estimated, since assessment of non-anthropogenic changes in carbon stocks in natural areas is beyond the protocol’s jurisdiction. However, the resultant data are suitable for assessing changes in woody vegetation cover (across areas greater than the 25 x 25 m pixel size) within many natural ecosystems, particularly ecosystems with a relatively open woody canopy and a naturally grassy understorey.

In this study we used the AGO’s GIS data layers of derived forest cover to estimate changes in woody cover within all lowland grassy woodland and coastal ecosystems in Victoria over a 16-year period from 1989 to 2005. In contrast to AGO analyses (AGO, 2002, 2005; Furby, 2002a), we document changes in woody cover *within* areas of native vegetation, not changes to the *extent* of native vegetation caused by either clearing or revegetation (although responses may include natural revegetation of previously disturbed natural ecosystems). We then compare these results against patterns of woody plant encroachment (or thinning) that have been documented in the published ecological literature.

MATERIALS AND METHODS

Study area

The State of Victoria occupies ca. 2.27 x 10^7 ha in south-eastern, mainland Australia. Annual average rainfall ranges from < 250 mm in the north-west of the state to > 1800 mm in the mountainous east (Bureau of Meteorology, unpubl. data). The Victorian Government’s state-wide typology of ‘Ecological Vegetation Classes’ (EVCs) defines 21 major vegetation groups by a combination of structural and environmental attributes (DSE, 2007). Four of these groups contain lowland grassy woodlands or coastal ecosystems (Table 1): Plains woodland, Herb-rich woodland, Riverine woodland and Coastal vegetation. Collectively these four ecosystems occupy 6.11 x 10^5 ha. Plains woodlands and Herb-rich woodlands occur on fertile soils on alluvial and volcanic plains across northern, central and southern Victoria. Average annual rainfall ranges from 400 to 650 mm. Riverine woodlands are restricted to watercourses, and are most extensive in northern and central Victoria. Coastal areas in the south of the state support a mosaic of Coastal woodlands, grasslands and shrublands. All of these ecosystems are now highly fragmented and surrounded by cleared agricultural areas. Changes in woody cover in agricultural areas are not analysed in this paper.

Landsat analyses

The following text briefly describes methods used by the AGO to obtain maps of woody forest cover. Comprehensive accounts are provided by AGO (2002), Furby (2002a, b), Furby & Woodgate (2002) and Lowell *et al.* (2003). As part of the National Carbon Accounting System (NCAS), the Australian Greenhouse Office (AGO) analysed Landsat images from 14 time periods between 1972 and 2005 to document changes in the extent of national forest cover. This paper is based on AGO analyses of images between 1989 and 2005 (i.e. the time periods 1989, 1991, 1992, 1995, 1998, 2000, 2002, 2004 and 2005), which were obtained from higher resolution Landsat TM and ETM^+ sensors rather than the earlier Landsat MSS sensors.

Images from 2000 were re-sampled to a 25 x 25 m pixel size and geometrically rectified and radiometrically calibrated to a consistent base before mosaicing to 1:1,000,000 map sheet tiles. Images from other time periods were then rectified and calibrated to the year 2000 base. Mosaiced Landsat scenes were stratified into landscape types based on forest type, landform and other factors. Woody forests were defined initially as stands possessing > 20% crown cover. Training sites covering the range of woody forest and non-forest cover types in each stratification zone were selected from aerial photographs. Canonical variate analyses were used to assign values to pixels in each training class, based on linear combinations of spectral bands which maximised differences between the training classes. Thresholds were developed to categorise pixels as woody forest, non-forest and uncertain, based on these values. Pixels assigned to woody forest, non-forest and uncertain categories by the thresholding process were then assigned a probability of forest cover. The probability images from each stratification zone were used in a multi-temporal analysis to identify areas of change in forest cover. Using conditional probability networks, the cover of pixels of uncertain cover in one year was inferred from earlier and later time periods. Maps of woody forest cover were then created for each time period (AGO, 2002; Furby, 2002a, b; Furby & Woodgate, 2002; Lowell *et al.*, 2003).

Vegetation analyses

We used ArcGIS ver. 9.2 (2006), S-Plus ver. 7.0 (2005) and SPSS ver. 14 (2006) for all spatial analyses. The AGO forest cover data were first converted from raster to vector format and clipped to the Victorian state boundary. These data were analysed in relation to the Victorian Ecological Vegetation Class (EVC) data layer provided by the Victorian Department of Sustainability and Environment (DSE, 2007). A total of 404 EVCs are recognised in Victoria, classed into 21 EVC groups. We calculated changes in the cover of woody vegetation in the four EVC groups (hereafter termed 'ecosystems') that contained lowland grassy woodlands or coastal ecosystems; the ecosystems in which encroachment has been commonly observed in single-site studies (Table 1). Additionally, to enable cover changes to be compared against a recent study of drought-induced tree canopy decline along the Murray River (Cunningham *et al*., 2007, 2009), Riverine woodlands were sub-divided into four regions: (1) lower Murray River, north-west of Echuca (= Murray Scroll Belt, Robinvale Plains and Lower Murray Fans zones in Cunningham *et al*., 2007, 2009); (2) central Murray and lower Goulburn Rivers (= Upper Murray Fans zone in Cunningham *et al*., 2007, 2009); (3) upper Murray River east of Yarrawonga and lower Ovens River (= Riverina zone in Cunningham *et al*., 2007, 2009); and (4) other Riverine forests in western and southern Victoria (not assessed by Cunningham *et al*., 2007, 2009).

The GIS map layer for all woodland and coastal ecosystems contained 65,731 polygons, totalling 6.11 x 10^5 ha in area. Polygon size was strongly skewed. Whilst 91% of all woodland and coastal polygons were $\leq$ 10 ha in area, polygons > 10 ha accounted for 87% of the total area.

Changes in the cover of woody vegetation were analysed at the ecosystem and polygon (patch) scales. Firstly, across and within all ecosystems, the total area of pixels classed as woody forest was summed to indicate the *extent of woody pixels* (in ha) within each ecosystem at each time period. This figure was then divided by the total area occupied by each ecosystem to give the *percentage cover of woody pixels per ecosystem*. Secondly, the percentage cover of woody pixels within each polygon was calculated to generate the *mean percentage cover of woody pixels per polygon* for each ecosystem in each time period.

The two analyses provide complementary information. Since a small number of large polygons account for most of the area in each ecosystem, changes in the extent of woody pixels and the percentage cover of woody pixels per ecosystem are strongly influenced by cover changes in a small number of large polygons. By contrast, changes in the mean percentage cover of woody pixels per polygon are independent of polygon size and indicate average changes across all polygons within each ecosystem. Such changes are more strongly influenced by cover changes in the large number of small polygons than in the small number of large polygons, and thereby represent more typical changes at the scale of individual patches.

Histograms were developed to show the frequency distribution of the amount of change in the percentage cover of woody pixels in each polygon in each ecosystem. Departures from normality in each frequency distribution were identified using Kolmogorov–Smirnov tests in SPSS ver. 14 (2006). All results are based on the entire population of vegetation polygons within each ecosystem rather than a sample. Thus, statistical tests to determine whether changes in characteristics of samples are likely to be significant across the entire population are not required. Consequently, should the mean percentage woody cover in an ecosystem increase from 73% to 75% during the study period, then this result represents the ‘real’ change in woody cover across the entire population (as indicated by Landsat analyses).

To identify how encroachment varied across geographic and climatic gradients, the percentage change in woody cover per polygon was compared against four geographic and climatic variables: latitude, longitude, mean annual temperature and mean annual precipitation. Encroachment was also compared against polygon area to identify how encroachment varied with patch size. Latitude and longitude were determined from the centroid of each polygon, and BIOCLIM estimates of mean annual temperature and rainfall were obtained from WORLDCLIM (2007). Correlations between environmental variables and the percentage change in woody vegetation cover from 1989 and 2005 were calculated using Spearman's rank correlation coefficient. A perfect negative relationship is obtained when $\rho = -1$, no relationship when $\rho = 0$, and a perfect positive relationship when $\rho = +1$ (Dytham, 2003). Stepwise linear regression [Step Akaike's information criterion (AIC) regression from the MASS library in S-Plus] was then undertaken to model changes in percentage woody vegetation cover in each polygon against all environmental variables. AIC values were compared to identify the best model. The above analyses were repeated for each and all (pooled) ecosystems.

We emphasise that all estimates of woody cover are based on the number of 25 x 25 m pixels identified as containing woody vegetation, not the canopy cover of individual trees. Additionally, increases in woody cover within a pixel beyond the 20% threshold would not be observed. Thus, small canopy gaps will not be identified and observed changes represent the infilling of large open gaps (>> 25 m diameter) by woody species. Analyses are unlikely to detect changes in woody cover in dense stands (where canopy gaps are < 25 m) or changes in the abundance of understorey shrubs beneath a dense canopy (e.g. Franco & Morgan, 2007). However, methods are suitable to document infilling of open woodlands and coastal ecosystems by woody plants, as has been reported in the literature from southern Australia (e.g. Withers & Ashton, 1977; Bren, 1992; Bennett, 1994; Costello *et al.*, 2000; Parker & Lunt, 2000). Botanical nomenclature follows Walsh & Entwisle (1994-1999).

RESULTS

Pooled across all four ecosystems, total woody vegetation cover (i.e. the extent of woody pixels) increased by 18,730 ha within the 6.11×10^5 ha study area over the 16-year period. Woody vegetation cover increased by > 7000 ha in each of the two most extensive ecosystems: Riverine woodlands and Plains woodlands. At a regional scale, 90% of the increase in total woody vegetation cover in Riverine woodlands occurred in the central Murray/lower Goulburn River and western/southern Victoria regions (Table 1). When averaged across all four ecosystems, the percentage cover of woody pixels increased by 3.0% during the time period (from 51.3% to 54.3%; Table 1), and ranged from +4.4% in Riverine woodlands to +1.9% in Herb-rich woodlands (Table 1). In Riverine woodlands in the central Murray/lower Goulburn River and western/southern Victoria regions, the percentage cover of woody pixels increased by 6.4% and 7.7%, respectively, while remaining relatively stable in the lower and upper Murray River regions (+0.7% and +2.3%, respectively).

Temporal changes in the extent of woody cover varied amongst ecosystems (Fig. 1). There was a significant linear increase in the extent of woody pixels in Riverine Woodland and Plains Woodland (Fig. 1): Change (ha) Plains Woodland = 350.06*years + 22.22, $r^2 = 0.75$, $P = 0.003$; Change (ha) Riverine Woodland: = 496.60*years + 468.80, $r^2 = 0.98$, $P < 0.001$. By contrast, the extent of woody pixels increased steadily from 1989 to 1995 in coastal ecosystems, but remained stable thereafter, and Herb-rich woodlands displayed an erratic trend (Fig. 1).

The above results document changes in total woody cover at the ecosystem scale. A slightly different picture emerges when changes are observed at the polygon (or patch) scale (Table 1). From 1989 to 2005, the mean percentage cover of woody pixels in each polygon increased by 7.3% (from 28.6% to 35.9%) when averaged across all four ecosystems, and by

≥ 5.9% in each ecosystem, with the maximum change occurring in Riverine woodlands (+9.2% cover of woody pixels per polygon). At a regional scale, the mean percentage cover of woody pixels in each polygon increased by 22% in Riverine woodlands in the central Murray/lower Goulburn River region. The greater increase in the percentage cover of woody pixels at the polygon scale compared to the ecosystem scale indicates that the woody cover increased to a greater extent in the many, small polygons than in the few large polygons.

Frequency distributions showing the amount of change in the percentage cover of woody pixels per polygon differed significantly from the normal distribution for all four ecosystems (Kolmogorov–Smirnov tests, all $P < 0.001$). All ecosystems had positively skewed distributions and were leptokurtic, with acute peaks around the mean and ‘fat tails’ (e.g. Fig. 2). Thus, more polygons experienced little or no change, fewer polygons experienced moderate change (positive or negative), and more polygons experienced large, predominantly positive, changes in percentage woody cover from 1989 to 2005, compared to a normal distribution.

Environmental variables

Spearman’s correlation coefficients between polygon size, geographic and climatic variables and the degree of change in the percentage cover of woody pixels per polygon were significant ($P < 0.001$) for all but three of 25 comparisons (Table 2). Large sample sizes undoubtedly contributed to the strong significance levels. However, all correlation values were low (Rho < 0.23), indicating weak associations between these environmental variables and the degree of woody plant encroachment per polygon. Associations between the degree of encroachment and longitude and polygon area were especially weak (Rho ≤ 0.1; Table 2).

For all (pooled) ecosystems, all five environmental variables (latitude, longitude, mean annual temperature and rainfall, and polygon area) were included in the best step-wise linear regression model between environmental variables and the degree of change in percentage cover of woody pixels per polygon. However this model accounted for just 1.2% of variation ($r^2 = 0.012$, F = 162.1, d.f. = 5,65714, $P < 0.001$), indicating that these attributes accounted for little of the variability in the degree of encroachment between polygons. Weak models (all $r^2 \leq 0.026$) were also obtained when each ecosystem was analysed separately: Coastal, $r^2 = 0.020$, F = 22.7, d.f. = 3, 3339, $P < 0.001$; Herb-rich Woodlands, $r^2 = 0.021$, F = 87.28, d.f. = 3, 12275, P < 0.001; Plains Woodlands: $r^2 = 0.012$, F = 150, d.f. = 3, 37097, $P < 0.001$; and Riverine, $r^2 = 0.026$, F = 68.36, d.f. = 5, 12991, $P < 0.001$. These results suggest that most of the variation in the degree of encroachment between polygons occurred at local scales rather than across broad geographic gradients. Polygon size had little influence on the degree of encroachment, despite sometimes substantial differences between changes in (1) the percentage cover of woody pixels per ecosystem, and (2) the mean percentage cover of woody pixels per polygon (Table 1).

DISCUSSION

These results suggest that encroachment patterns reported from previously studied, single-site studies are indicative of more widespread changes across lowland woodland and coastal ecosystems in south-eastern Australia. At the scale of observation, woody vegetation cover increased in all four ecosystems over the 16-year period. The degree of increase varied between ecosystems, being twice as great in Riverine woodlands as in Herb-rich woodlands when assessed at the ecosystem scale. However, at the polygon scale, the mean change in the percentage cover of woody pixels was less varied across all four ecosystems, ranging from +5.9 to 9.2%. Additionally, there was considerable variability in the degree of change in woody cover within individual polygons, indicating that woody plant cover has not increased in all stands over time; many patches have remained stable or become more open.

The cover changes documented here cannot be directly compared with those of previous studies owing to different sampling periods and survey resolutions. Most studies of woody plant encroachment in Victoria document earlier or longer-term changes in single, often relatively small sites (e.g. Bren, 1992; Bennett, 1994; Lunt, 1998a; Parker & Lunt, 2000; Emeny, 2006; Franco & Morgan, 2007; Gent & Morgan, 2007; Price & Morgan, 2009), and many document encroachment at finer spatial resolutions, including increases in understorey shrubs beneath tree canopies (Emeny, 2006; Franco & Morgan, 2007; Price & Morgan, 2009), which are unlikely to be observed in this study. However, these trends are consistent with changes identified in many single site studies from Victoria. A number of studies have documented increases in woody cover in Coastal vegetation (Bennett, 1994; Emeny, 2006; Larchin, 2007; plus Costello *et al.*, 2000, north of Victoria), and Riverine (Bren, 1992) and non-riverine woodland ecosystems (Lunt, 1998a; Parker & Lunt, 2000; Robinson, 2006; Franco & Morgan, 2007; Price & Morgan, 2009). In the following sections, we first qualify the results obtained and then compare these results against findings from earlier studies that documented changes in woody cover in Victoria and elsewhere in Australia.

Caveats

In this study we used the woody vegetation cover layer developed by the AGO's NCAS programme to assess cover changes within patches of native vegetation, without undertaking further ground-truthing. We have adopted this approach for a number of reasons. Firstly, the woody cover GIS layers that we used form the basis of Australia's national carbon accounting system, and development of these datasets by the AGO incorporated an extraordinarily detailed process (which few research groups could hope to replicate), including rigorous quality control processes and multiple levels of ground truthing (see e.g. technical manuals by AGO, 2002; Furby, 2002a, b; Furby & Woodgate, 2002; Lowell *et al.*, 2003). Furthermore, we restricted our analysis to 1989–2005, rather than the longer 1972–2005 period for which NCAS data were available, to eradicate any possible errors that may have arisen during the transition from the earlier Landsat MSS sensors, to the later Landsat TM and ETM^+ sensors. All results in this paper are based solely on the later Landsat TM and ETM^+ data. Whilst the results undoubtedly contain a degree of noise, steady ongoing increases in cover in ecosystems such as Plains woodlands and Riverine woodlands are difficult to explain in terms of random or systematic errors.

More recently, Grant (2008) compared the accuracy of the AGO's NCAS Landsat data (as used in this study) against aerial photographs in three vegetation types in central Victoria (Riverine Woodlands, Plains Woodlands and Box-Ironbark Forests). Despite considerable variability at the individual polygon level, when data were pooled across polygons, the two methods gave surprisingly similar estimates of mean woody vegetation cover per polygon (45% cf. 46% cover based on photos and Landsat images obtained from 1972 to 1988, and 67% by both methods based on photos and Landsat images obtained from 1989 to 2005, illustrating substantial encroachment during the period). Consequently, Grant (2008) concluded that the AGO's Landsat data provided an accurate indication of changes in woody cover at regional scales.

Nevertheless, the most cautious reading of the results is as a set of hypotheses relating to previously unassessed broad-scale changes in ecosystem properties that require more detailed examination. A key strength of this broad-scale approach is the capacity to identify ecosystems and areas where changes appear to have been most substantial, in order to stratify and select sites for more detailed studies of changes in particular ecosystems or regions.

Riverine woodlands

The large increase in woody cover in Riverine woodlands was unexpected as only one study has reported increases in tree cover in riverine areas in Victoria. Bren (1992) attributed encroachment by *Eucalyptus camaldulensis* into grassy plains in Barmah Forest in northern Victoria to reduced seedling mortality following river regulation, but did not mention increases in tree cover in other riparian areas. Our results indicate substantial increases in woody plant cover in riverine woodlands in the central Murray River and upper Goulburn River region, which includes, but is considerably larger than, Bren's (1992) study area. However, woody plant cover also increased in Riverine forests in western Victoria (+7.7% cover), which has not been noted previously. Regeneration of the dominant riverine trees, *E. camaldulensis* and *E. largiflorens*, is strongly episodic, with dense and widespread regeneration pulses after major floods (Dexter, 1978; Cunningham *et al.*, 1981). Additionally, tree regeneration in riverine areas is widely constrained by heavy livestock grazing (Robertson & Rowling, 2000; Jansen & Robertson, 2001) and stocking levels have declined in many riparian ecosystems on private and public land over the past 30 years (ECC, 2001; Price & Lovett, 2002). The increase in cover we detected may include regeneration during the study period as well as canopy growth of older saplings and trees.

The trend of increasing tree cover in Riverine woodlands contrasts with recent reports of a decline in tree health and high levels of tree mortality along the Murray River since the 1980s, owing to drought and water extraction (Lane *et al.*, 2005; Cunningham *et al.*, 2007, 2009). Cunningham *et al.* (2007, 2009) found that stand health and tree mortality varied regionally along the Murray River. Stands in north-central Victoria (including sections of the Murray, Ovens and Goulburn Rivers) were healthier than those in semi-arid, north-west Victoria and South Australia. These patterns are similar to those observed in this study. We found that woody plant cover increased substantially over 16 years in the central Murray and upper Goulburn River region, where Cunningham *et al.* (2007, 2009) found that stands were relatively healthy. By contrast, tree densities remained relatively stable in areas of the lower Murray River, where tree health has declined most severely in recent years (Cunningham *et al.,* 2007).

Non-riverine woodlands

The documented increase in woody cover in non-riverine and non-coastal grassy woodlands (Plains woodlands and Herb-rich woodlands) is consistent with reported increases in tree and shrub cover in single-site studies (Lunt, 1998a; Parker & Lunt, 2000; Franco & Morgan, 2007; Price & Morgan, 2009). Ecological studies of changing stand structures in grassy woodlands have documented encroachment by *Allocasuarina littoralis* (Lunt, 1998a), *Callitris glaucophylla* and *Eucalyptus* species (Parker & Lunt, 2000) and the understorey shrubs, *Leptospermum scoparium* (Price & Morgan, 2006, 2009) and *Acacia paradoxa* (Franco & Morgan, 2007). The changes documented in this study are likely to reflect changes in the abundance and cover of dominant *Eucalyptus* species rather than smaller shrubs, since the 25 m pixel size precludes observations of understorey shrubs beneath relatively dense tree canopies. However increases in shrub cover may contribute to trends where shrubs occur between tree canopies and the net cover of trees and shrubs crosses the 20% cover threshold.

Curiously, few studies from non-riverine woodlands in Victorian have documented changes in *Eucalyptus* cover. Parker & Lunt (2000) noted a marked increase in *Eucalyptus melliodora* and *E. microcarpa* in a mixed *Eucalyptus–Callitris* woodland in northern Victoria, and Robinson (2006) and Grant (2008) reported large increases in *Eucalyptus* cover in central Victoria following land-use change from production agriculture and grazing to rural residential landuse. Our field observations indicate widespread infilling of *Eucalyptus* species in woodlands, especially in north-central Victoria (authors, pers. observ.). Similarly, Dorrough & Moxham (2005) recorded *Eucalyptus* regeneration in 91% of quadrats on public land in north-central Victoria, at unspecified densities. Further broad-scale field surveys of woody plant encroachment in woodlands are required to document the ecosystems and species undergoing most marked changes.

Compared to the steady increases in woody cover in other ecosystems, woody cover varied erratically in Herb-rich Woodland, including a major decline (1114 ha) between 1995 and 1998 (Fig. 1). This decline was dispersed across more than 2000 polygons, and the largest decline in woody cover within a single polygon was just 46 ha. The cause of this apparent decline is unknown, and it does not appear to be due to burning or clearing.

Coastal ecosystems
The increase in woody cover in Coastal ecosystems supports suggestions from some single-site studies (e.g. Lunt, 1998a, b) that woody vegetation cover has increased in recent decades across large areas of coastal vegetation. This increase includes a range of native trees and shrubs such as *Acacia longifolia* (syn. *Acacia sophorae*), *Allocasuarina littoralis*, *Leptospermum laevigatum* and other species, and also exotic shrubs such as *Chrysanthemoides monilifera* and *Polygala myrtifolia* (Blood, 2001; Muyt, 2001). Increases in woody cover have occurred in a variety of coastal and near-coastal vegetation types, including grasslands, shrublands, heathlands and woodlands (Bennett, 1994; Lunt, 1998a; Costello *et al.*, 2000; Emeny *et al.*, 2006; but see Gent & Morgan, 2007). Thus, the increase in woody cover documented in this study appears to be part of a widespread, longer-term trend. Inspection of aerial photographs from the 1940s shows that many areas that now have a closed vegetation canopy were far more open 60 years ago, when bare, open dune blowouts were far more common (authors, pers. observ.).

Transient versus persistent changes
The observed changes in woody cover incorporate transient and more persistent longer-term changes. In individual patches, transient changes include the loss and subsequent re-establishment of woody cover following disturbances such as fires and timber harvesting. However, at the state-wide scale, the steady increase in woody cover in Riverine woodland, Plains woodland and Coastal vegetation is more likely to reflect a persistent, longer-term process. Large wildfires are rare in fragmented woodlands in Victoria (Lunt & Bennett, 2000), and have not occurred in most areas during or immediately before the study period. Instead, ongoing increases in tree densities in these ecosystems are more likely to be responses to regional changes in land use and disturbance regimes (see below). Since persistent changes in woody vegetation structure can have major impacts on ecosystem

processes and composition, further examination of the causes, patterns, and impacts of these persistent increases is warranted.

Continental comparisons

How do trends in woody vegetation cover in south-eastern Australian woodlands compare to other Australian regions? Regional studies of vegetation changes over 20-50 years in savannas in northern Australia present a variety of trends, including relatively stable (Sharp & Bowman, 2004), fluctuating (Lehmann *et al*., 2008), minor increases (5-10%) similar to those found in this study (Fensham *et al*. 2003), and substantial (> 20%) increases in woody cover (Crowley & Garnett, 1994; Sharp & Whittaker, 2003; Brook & Bowman, 2006). The greatest increases in cover occurred where dominant species and ecosystem structure were transformed, as in transitions from savannas and grassy forests to closed rain forests (e.g. Harrington & Sanderson, 1994; Brook & Bowman, 2006) and treeless grasslands to dense shrublands (Crowley & Garnett, 1994).

Extreme ecosystem transitions such as these do not appear to occur across large scales in lowland woodlands in south-east Australia. Instead, most examples of densification appear to involve infilling by existing canopy or understorey dominants (e.g. Parker & Lunt, 2000; Grant, 2008; Price & Morgan, 2009), although more marked examples do occur (e.g. Bren, 1992). Uncleared semi-arid woodlands in north-eastern Australia exhibit trends similar to those found in our study. Fensham *et al*. (2003) reported a 5.2% increase in tree cover (from 24.9 to 30.1%) over 44 years (1951-1995). This period included a severe recent drought that caused substantial tree mortality (Fensham & Holman, 1999). In south-eastern Australia, protracted drought conditions over the last decade have not yet led to widespread declines in woody plant cover in lowland woodlands and coastal ecosystems; instead, woody vegetation cover has continued to increase during this period. However, tree health has declined dramatically in drought-stricken riverine ecosystems (Cunningham *et al*., 2007, 2009).

Causes of changes

As elsewhere across the globe (Archer, 1995; Fensham & Fairfax, 1996; Noble, 1997; Scholes & Archer, 1997; Briggs *et al.*, 2005), increases in woody plant cover in natural ecosystems in south-east Australia have been attributed to a variety of causes (commonly acting together) including removal of livestock grazing, heavy grazing by non-browsing herbivores, changed fire regimes (especially long inter-fire periods), soil disturbance, changed timber harvesting and flooding regimes, periods of high rainfall, and climate change (Withers & Ashton, 1977; Bren, 1992; Bennett, 1994; Lunt, 1998a; Costello *et al.*, 2000; Parker & Lunt, 2000; Wearne & Morgan, 2001; Spooner *et al*., 2002; Spooner *et al.*, 2004; Dorrough & Moxham, 2005; Watson, 2005; Emeny *et al.*, 2006; Robinson, 2006; Franco & Morgan, 2007; Price & Morgan, 2009).

Only one study (Wearne & Morgan, 2001) has attributed increases in woody vegetation cover in south-east Australia to climate change (although most studies were conducted before climate change was widely recognised). Climate change can influence vegetation growth and cover changes directly as well as indirectly through changes to disturbance regimes such as fire and flooding (Bond & Midgley, 2000; Hennessy *et al.*, 2005; Dunlop & Brown, 2008). Unfortunately, it is exceedingly difficult to separate the effects of climate change from widespread changes to land use and disturbance regimes. Since the 1970s, land management across Victoria has changed enormously (Lunt & Spooner, 2005; Clode, 2006). Large areas of public land have been declared as conservation reserves, typically resulting in livestock removal and changes to disturbance regimes including soil disturbance, fires and timber harvesting. Management of native vegetation on private land has also changed in many regions, especially where land use has changed from agricultural production to rural residential use, as in coastal and central Victoria (Barr, 2005). Robinson (2006), for instance, attributed a 70% increase from 1971 to 1996 in the area of Box-Ironbark forest in two catchments in central Victoria to the change from production agriculture to rural residential land use. Interactions amongst changes in land use, disturbance regimes and climate will continue to be extremely important in affecting vegetation patterns (Dunlop & Brown, 2008), but will continue to be challenging to disentangle.

Conclusions

Results from this study suggest that recent increases in woody vegetation cover have been widespread in lowland grassy woodlands and coastal ecosystems in Victoria. This raises a number of important questions for future research and management, since increases in woody vegetation cover can have marked effects on ecosystem structure, composition and function. Further studies are required to identify the processes driving persistent changes to vegetation structure, the impact of these changes on socially-contested environmental services and ecosystem processes (e.g. water, fire, carbon and biodiversity), ways to manage persistent structural changes (where required), and the impact of ongoing global warming on future changes to vegetation structure.

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Biosketch

Ian Lunt is an Associate Professor in vegetation and disturbance ecology at Charles Sturt University, Albury. He has published widely on the disturbance ecology and management of fragmented and endangered grassland and woodland communities. His major research interests concern the impacts of human disturbances on altered ecosystems.

Author contributions: I.L., J.W. and R.D conceived the ideas; L.W. and R.D collated the AGO NCAS data; S. McD, L.W. and I.L. analysed the data; I.L., L.W and J.W wrote the manuscript.

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Figure captions

Figure 1 Temporal changes in the extent of woody vegetation cover (in ha) in four lowland woodland ecosystems in Victoria, Australia, from 1989 to 2005, as detected by the Australian Greenhouse Office's National Carbon Accounting System (NCAS) Landsat analyses. Note the different scales on the *y*-axes.

Figure 2 Frequency distribution showing variation in the amount of change in the percentage cover of woody pixels in each polygon in Riverine woodlands in Victoria, Australia, from 1989 to 2005 (n = 12,997 polygons). Similar distributions occurred for all four woodland ecosystems that were analysed.

Fig. 1

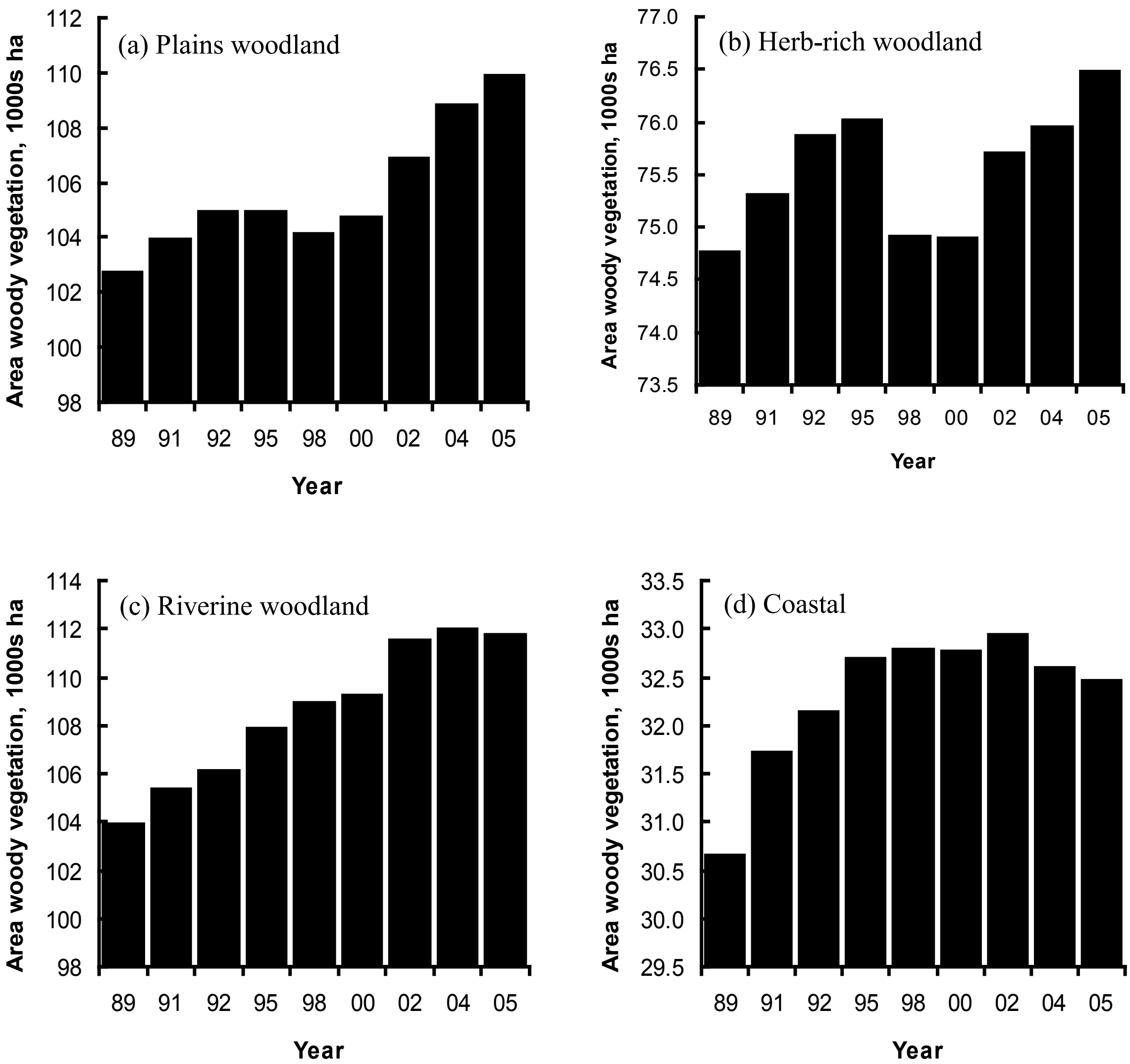
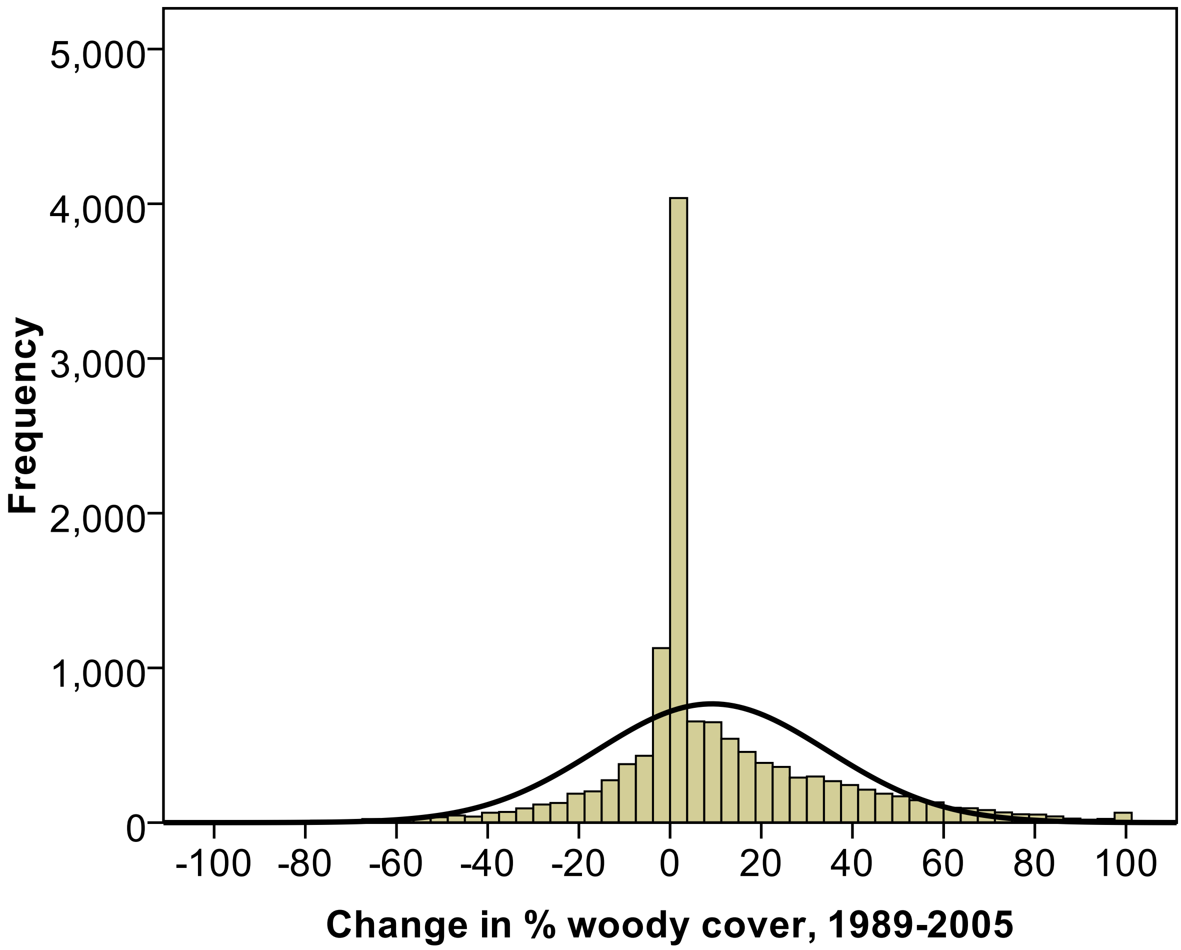

(a) Plains woodland
(b) Herb-rich woodland
(c) Riverine woodland
(d) Coastal
Area woody vegetation, 1000s ha
Year
89 91 92 95 98 00 02 04 05
98 100 102 104 106 108 110 112
73.5 74.0 74.5 75.0 75.5 76.0 76.5 77.0
98 100 102 104 106 108 110 112 114
29.5 30.0 30.5 31.0 31.5 32.0 32.5 33.0 33.5

Fig. 2



5,000
4,000
3,000
2,000
1,000
0
Frequency
-100
-80
-60
-40
-20
0
20
40
60
80
100
Change in % woody cover, 1989-2005

Table 1 Changes in the extent and percentage cover of woody vegetation cover in woodland ecosystems in Victoria, Australia, from 1989 to 2005.

Ecosystem	Number Polygons	Ecosystem Area (ha)	Extent Woody Pixels (ha)			Percent Cover of Woody Pixels Per Ecosystem			Mean Percent Cover of Woody Pixels Per Polygon				
			1989	2005	Change	1989	2005	Change	1989	2005	Change	SD	CV
Plains Grassy Woodlands	37,101	290,260	102,688	109,851	7,164	35.4	37.8	2.5	22	28	6.7	24.2	364
Herb-rich Woodlands	12,279	90,741	74,759	76,473	1,714	82.4	84.3	1.9	42	50	7.6	27.8	364
Coastal Woodland, Grassland & Shrubland Complex	3,343	46,569	30,647	32,455	1,808	65.8	69.7	3.9	34	40	5.9	23.3	394
Riverine Grassy Woodlands	13,008	183,694	106,126	114,170	8,044	57.8	62.2	4.4	33.9	43.1	9.2	25.3	276
Lower Murray River	683	67,153	27,307	27,792	485	40.7	41.4	0.7	37.0	38.9	1.8	14.8	817
Central Murray River/ upper Goulburn River	3,311	59,579	46,733	50,573	3,840	78.4	84.9	6.4	36.3	58.2	21.9	28.6	131
Upper Murray River	1,188	12,589	8,371	8,655	284	66.5	68.7	2.3	39.5	42.8	3.3	20.5	622
Western & southern Victoria	7,826	44,373	23,715	27,150	3,436	53.4	61.2	7.7	31.8	37.2	5.4	23.3	435
Total	65,731	611,264	314,220	332,949	18,730	51.3	54.3	3.0	28.6	35.9	7.3	25.1	344

SD = standard deviation, CV = coefficient of variation

Table 2 Spearman's rank correlation coefficients between the degree of woody plant encroachment (change in the percentage cover of woody pixels per polygon) in four woodland ecosystems in Victoria, Australia, between 1989 and 2005 and geographic and climatic variables and polygon area. All correlations were significant at $P < 0.001$ unless indicated, 'ns' = not significant.

		Spearman's Correlation Coefficient (Rho)				
Ecosystem	Number polygons	Latitude	Longitude	Mean annual rainfall	Mean annual temperature	Polygon area
Coastal complex	3,343	-0.03 ns	-0.09	0.07	0.02 ns	0.06
Herb-rich Woodlands	12,279	0.07	-0.10	-0.09	0.003 ns	-0.03
Plains Grassy Woodlands	37,101	0.18	-0.02	-0.14	0.16	0.04
Riverine Grassy Woodlands	13,008	0.20	0.06	-0.14	0.23	0.08
All Ecosystems	65,731	0.16	-0.03	-0.13	0.14	0.04