Ecological effects of harvesting in Victoria's native forests: quantification of research outputs

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Summary

We quantified all research documents, released prior to mid-2002, that contain unique assessments of ecological effects of timber harvesting practices in the native commercial forests of Victoria. The frequency and diversity of research increased after the 1970s and particularly in the 1990s, consistent with trends in public demand for information. This, together with a strong correlation between research activity in each forest type and current volumes of extracted timber, reflected a strong management focus in forest research. Nonetheless, most studies were not part of large coordinated research programs (60% of documents), and spanned less than three years (61%). Studies were overwhelmingly conducted at the scale of individual sites (79%). Many documents were in the form of unpublished, internal reports (i.e. not externally and independently reviewed; 38%). Categorisation by forest type, harvesting practice and biological response variables shows negligible to minimal research of current and recent harvesting practices in river red gum and box-ironbark forests. Categorisation also shows negligible to minimal research into the ecological effects of four current harvesting practices in high-elevation mixed-species forest, and of non-standard practices in most forests. Studies of harvesting effects on the soil, water and physical environment are few in most forests, particularly for harvesting practices other than clearfelling. In contrast, traditional interests in tree regeneration and growth are more evenly represented across forests and practices. Considerable scope remains to increase the diversity of research on harvesting effects in native forests. We argue that studies should not be isolated but placed in broader contexts that increase research efficiency and data longevity, and enable objective assessment of ecological theories on harvesting effects.

Keywords: forest management; research policy; applied research; biological indicators; environmental impact; forest ecology; literature reviews; logging; silviculture; *Eucalyptus*

Introduction

Reflecting changing social values, the concept of forest sustainability has evolved from a traditional focus on perpetual wood supply to include broader ideals of ecosystem vitality (Chikumbo *et al*. 2001). In Australia, the result has been widespread commitment to 'ecologically sustainable forest management' (ESFM) — the provision for all social, economic and environmental forest values including

> the maintenance of the ecological processes that sustain forest ecosystems, the conservation of the biological diversity associated with forests … and the protection of water quality and associated aquatic habitats (Commonwealth of Australia 1992).

Commitment to ESFM in Victoria is enacted through a broad framework of legislation and policy, and a comprehensive hierarchy of strategic and operational plans (Commonwealth and Victorian Regional Forest Agreement Steering Committee 1996). Key components are those guiding timber production activities — including the 'Code of Forest Practices for Timber Production', Forest Management Plans, Regional Prescriptions, and Forest Coupe Plans (Department of Natural Resources and Environment 1996). Each stage is underpinned by operational experience, broad ecological principles (see Abbott and Christensen 1994), and applied research. Of particular relevance is research that assesses ecological effects of harvesting since it has potential to refine guidelines and prescriptions, guide and review policy and planning (Davey *et al*. 1997), improve monitoring and auditing protocols (e.g. Standards Australia 2002), identify and evaluate ESFM criteria and indicators at a range of scales (Raison *et al.* 1997), and develop clear statements of uncertainty (*sensu* Hilborn and Ludwig 1993).

In this paper, we categorise and quantify research documents that contain assessments of ecological effects of timber harvesting practices in Victoria's native forests. We aim to:

- summarise the nature of research in terms of the type, duration and spatial scale of studies, and the proportion of documents that were externally reviewed and published; and
- describe the frequency of research by forest type, harvesting practice and ecological response variable.

The data are used to illustrate trends in native forest research in Victoria since the 1930s, and to highlight gaps in knowledge of harvesting effects. In a companion paper (Bennett and Adams 2004), we evaluate the experimental rigour of a major sub-set of the research documents. Here, we combine findings from both papers to indicate potential subjects for future research, and to highlight mechanisms in the research process that facilitate the integration and coordination of data from different studies.

Methods

Scope

This paper is the first part of a review, the aim of which was to evaluate all published and unpublished research documents, released prior to June 2002, that contain assessments of ecological effects of timber harvesting practices in the native commercial forests of Victoria. We did not evaluate operational performance (e.g. Department of Natural Resources and Environment 2002), nor management systems and processes (e.g. Commonwealth and Victorian Regional Forest Agreement Steering Committee 1996).

Potentially relevant documents were identified from individual reference lists, electronic databases (e.g. 'Current Contents'; 'Agricola'), and bibliographies of scientific literature (e.g. King *et al.* 1994; Incoll *et al.* 1997; Murphy *et al.* 1998). From over 1000 potentially relevant documents, we identified 292 core documents for categorisation. The remaining documents are either irrelevant or were classified as 'background' (e.g. description of forests, practices or policies; evaluations of harvesting practices from economic, logistical or social viewpoints) or 'ancillary' (e.g. ecological or management studies that inform practices but do not assess the ecological effects of their implementation). Some 79 documents were classified as 'proxy' on the basis that they repeat data from related core documents and contain negligible additional data. Relative to core documents, proxies are generally not peer-reviewed, contain less data, or are less accessible.

Core documents met the following selection criteria:

- Data and/or interpretations are original or unique;
- Forest types are those commercially harvested in Victoria (most forest types are not confined to Victoria and relevant documents from other south-eastern States were included);
- Ecological effects of past, current and potentially-available harvesting or associated practices (e.g. seedbed preparation) were examined. Effects were either directly measured after harvesting activities, predicted through models, or inferred through comparisons with 'natural' or 'non-manipulated' systems (e.g. density of hollow-bearing trees in unharvested landscapes). Reviews or commentaries were included only if they presented unique scientific perspectives (i.e. were not simply summaries of other documents).

All core documents were categorised in a custom-made reference database (available from the first author), which allowed quantification by combinations of the three primary fields — forest type, harvesting practice and biological response variable (defined below). Initially, other fields were included such as site preparation practice, regeneration practice and treatment of residual wood. However, information on these fields was frequently not provided and they were not further considered.

Forest types

We used a broad 'silvicultural' classification of forest types based on the dominant eucalypt species, because it or similar systems form the basis of policy, operational and research documents relevant to harvesting practices in Victoria (e.g. Campbell *et al.* 1984; Department of Natural Resources and Environment 1998; Murphy *et al.* 1998; Lutze *et al.* 1999). These forest types include ash forests of the central and eastern highlands (dominated by mountain ash or alpine ash), mixed species forests of the highlands, foothills and coastal plains (low-elevation mixed species (LEMS) and high-elevation mixed species (HEMS) dominated by a range of eucalypts), and box-ironbark and river red gum forests of the northern plains (Table 1). Under other classification systems, each forest type may represent a number of floristic and structural communities. For example, LEMS can include 'Foothill mixed species' and 'Coastal mixed species' (Flinn and Bales 1990); 'Open forest II' and 'Open forest III' (e.g. Land Conservation Council 1985); 'Damp', 'Dry', 'Lowland' and 'Coastal' sclerophyll forest (Flinn and Bales 1990; Bartlett and Lugg 1993); and 'Lowland forest' and 'Shrubby dry forest' (Woodgate *et al.* 1994).

LEMS forests are the most widely distributed native forests in Victoria and, together with HEMS forests, yield the greatest

Table 1. 'Silvicultural' system used to classify Victoria's native, commercial forests (from Lutze *et al.* 1999). 'General mixed species' was used if insufficient information was available to categorise forest as LEMS or HEMS, and 'General' was used if no particular forest type was specified.

Forest type	Distribution (and dominant *Eucalyptus* species)
Low-elevation mixed species (LEMS)	Altitude <700 m; foothills of Great Dividing Range and on coastal plain; dominant eucalypts often <40 m in height (*E. obliqua–E. radiata*, *E. dives–E. cypellocarpa*, *E. viminalis*, *E. rubida*; *E. sieberi–E. globoidea*)
High-elevation mixed species (HEMS)	Altitude 700–1000 m; eastern highlands and southern areas (down to 150 m in moist gullies); dominant eucalypts often >40 m in height (*E. obliqua*, *E. cypellocarpa*, *E. viminalis*, *E. dalrympleana*, *E. dives*, *E. radiata*, *E. fastigata*, *E. denticulata*, *E. globulus*)
Mountain ash	Central and eastern highlands, Otway ranges and South Gippsland; altitudes 120–1100 m; annual rainfall >1000 mm (*E. regnans*)
Alpine ash	Sub-alpine zone (>1000 m altitude) of central and eastern highlands (*E. delegatensis*)
River red gum	Broad flood plains near the Murray River (northern Victoria); semi-arid climate; annual rainfall 350–450 mm (*E. camaldulensis*)
Box-ironbark	North-central Victoria; altitude 200–400 m; annual rainfall 400–700 mm (*E. tricarpa*, *E. microcarpa*, *E. leucoxylon*, *E. polyanthemos*, *E. melliodora*, *E. goniocalyx*, *E. macrorhyncha*)
General mixed species	As for LEMS or HEMS
General	Any of the above

Table 2. Timber volume and value (2000/01), area harvested (2000/01; see Table 3), and area in State Forest (2002) for each forest type. 'S' and 'R' indicate sawlogs and residual logs. Separate volume and value data for LEMS and HEMS were not available. 'Total' includes other timbers and forest types. Data were derived from 'Log Sales System' and 'State Forest Resource Inventory' (Department of Sustainability and Environment).

Forest type	Volume ('000 m^3)		Value ('000 AUD)		Harvested area (ha)	State Forest ('000 ha)
	S	R	S	R		
Mixed species	372	452	7 077	1 233	–	–
LEMS	–	–	–	–	6 960	1 490
HEMS	–	–	–	–	2 355	350
Mountain ash	229	542	8 977	3 207	1 215	125
Alpine ash	137	179	4 586	816	990	160
River red gum	8	0.7	328	13	4 050	100
Box-ironbark	0.7	0.7	30	31	2 430	170
Total	747	1 570	21 032	6 733	18 000	3 315

volume of sawlog timber per year (Table 2). However, if combined the mountain ash and alpine ash forests usually yield almost as much sawlog, much more residual log, and certainly the greatest value of timber per year, reflecting greater productivity and average royalty rates (Table 2).

Harvesting practices

A broad diversity of native forest types in Victoria (Table 1) has led to the implementation of a range of harvesting practices (Table 3). Current and potentially-available practices for each forest type are described in 'Forest Management Plans' (e.g. Department of Natural Resources and Environment 1998) and regional prescriptions (e.g. Department of Natural Resources and Environment 1997). Victoria's 'Code of Forest Practices for Timber Production' provides broad goals and guidelines for harvesting (Department of Natural Resources and Environment 1996), and 'silviculture' guidelines provide details on operational techniques and procedures (e.g. Sebire and Fagg 1997; Lutze and Geary 1998), and outline mechanisms for decision-making (e.g. Ryan 1997).

Briefly, most harvesting practices can be described in terms of two continua related to pattern of tree removal (after Campbell 1997). These are (a) the opening or gap size (Clearfell > Group selection > Single tree selection) and (b) the density of retained trees (Clearfell < Seedtree < Shelterwood ≤ Retained overwood ≤ Coppice with standards). Harvesting practices can also be defined in terms of the age-class structure of subsequent tree regeneration. Thus, practices such as Clearfell and Seedtree, which involve widespread regeneration in a single age-class, are termed 'even-aged' practices, while those that involve staggered removal of trees in sequential felling cycles are termed 'uneven-aged' practices (e.g. Group selection, Single tree selection — Squire *et al.* 1991; Department of Sustainability and Environment 2003). In thinning operations, where tree regeneration is not an objective, practices are principally defined according to the utilisation (Commercial thinning) or not (Non-commercial thinning) of felled stems. Our definition of Clearfell modified encompassed recently proposed changes to Clearfell harvesting involving retention of vegetation for environmental purposes in addition to that normally retained (e.g. retention of understorey 'islands'; Ough and Murphy 1998). Lastly, practices were defined as 'General' when harvesting effects were broadly evaluated but a particular practice was not specified.

Dominant, recent harvesting practices are Seedtree in LEMS and HEMS forest, Clearfell in mountain ash and alpine ash forest, Single tree selection in river red gum forest, and Commercial

Table 3. Recent harvesting practices in Victoria's native, commercial forests. Data are hectares treated in 2000/01 (from 'Annual Report Database', Department of Sustainability and Environment). 'Shelterwood' includes first and second fellings, and 'Single tree selection' includes 'Coppice with standards'.

Forest type	Harvesting practice						Total
	Clearfell	Seedtree	Shelterwood	Group selection	Single tree selection	Commercial thinning	
LEMS	315	4 465	405	335	400	1 040	6 960
HEMS	35	1 770	465	0	25	60	2 355
Mountain ash	1 130	70	0	0	0	15	1 215
Alpine ash	915	5	0	0	0	70	990
River red gum	0	0	0	0	3 095	955	4 050
Box-ironbark	0	0	0	0	330	2 100	2 430
Total	2 395	6 310	870	335	3 850	4 240	18 000

Table 4. Groups of biological response variables (listed in decreasing order within groups according to the total number of core documents to contain assessments of ecological effects of harvesting practices)

Group	Response variables
Growth	Tree regeneration; Tree growth; Nutrient capital; Seed production; Other aboveground biomass; Below-ground biomass; Total ecosystem biomass; Tree physiological processes
Diversity	Vegetation structure; Vertebrate abundance and behaviour; Plant species numbers; Invertebrates; Plant genetics; Vertebrate genetics
Health	Plant health; Pathogens; Introduced flora; Keystone species or groups; Connectivity; Introduced fauna
Soil	Physical; Chemical; Biological
Water	Water volume; Water quality; Riparian zones
Physical environment	Micro-climate; Gas emissions; Fire regimes

thinning in box-ironbark forest (Table 3). Tree removal is often followed by site preparation that, in broad terms, involves additional mechanical disturbance or, more commonly, burning (for details see Lutze and Geary 1998). Additional site preparation is not usually required in river red gum and box-ironbark forest, and is often unnecessary in LEMS forest due to adequate eucalypt stocking or seedbed distribution after harvesting alone (Annual Report Database 2000/01, Forestry Victoria). A range of practices and processes contributes to tree regeneration including natural seedfall (dominant in river red gum forest), aerial sowing (mountain ash, alpine ash and HEMS), induced seedfall (LEMS) and coppice (box-ironbark — Annual Report Database 2000/01, Forestry Victoria).

Biological response variables

Biological response variables were used to represent the full range of ecosystem parameters and processes. These were defined from ecological literature (e.g. Kohm and Franklin 1997; Perry 1998; Aber *et al.* 2000), and from ecological principles and criteria for sustainable forest management developed through (i) the Montreal Process (Commonwealth of Australia 1998), (ii) Regional Forest Agreement processes (e.g. Commonwealth and Victorian Regional Forest Agreement Steering Committee 1996), (iii) the Forest Stewardship Council (Forest Stewardship Council 2000), and (iv) The Australian Forestry Standard (Standards Australia 2002). In total, 29 response variables were defined. These were divided into 6 groups as indicated in Table 4.

Results and discussion

Document status and scope

The first of the 292 core documents was released in 1934 (Ferguson 1934). Most documents (89%) were released after the 1970s, with 52% released between 1990 and 1999 (data not shown). This increase from 1980 followed increased public concern and demand for information throughout the 1970s about the environmental impacts of harvesting in Australia's native forests (Dargavel 1995). It is consistent with a nationwide survey that found a marked increase in the 1980s in the number of published papers examining ecological effects of forest use in Australia (Resource Assessment Commission 1993).

Most core documents (62%) are published — that is, they appear in peer-reviewed books, journals, reports, theses and conference proceedings. The proportion of published documents differs between forest types — from 33% in HEMS forest to 76% in alpine ash forest (Table 5). Non-reviewed (i.e. 'unpublished') documents are mainly 'internal' research reports within government agencies. Their prevalence reflects a common management focus in forest research. Lack of external review of such 'management studies' could increase risks of erroneous conclusions and inappropriate management actions (Johnson 2002). Indeed, our evaluation of a sub-set of studies relevant to LEMS and mountain ash forests found errors in statistics and experimental design in about half of those examined, albeit irrespective of publication status (Bennett and Adams 2004). Perhaps of greater consequence is the predominance of research based on individual studies (60% of documents; Table 5), since it is likely that these had fewer resources, less continuity, and less

Table 5. Total number of documents that contain research on ecological effects of harvesting practices within each forest type, and the proportions that are published (i.e. externally reviewed), are individual studies (i.e. not obviously part of a larger research program), contain data that span ≤3 or >10 y, and that contain data at the scale of individual sites (i.e. coupes or forest stands) or at broader scales (i.e. catchments or regions)

Forest type	Total	Proportion of total (%)					
		Published	Individual study	Duration ≤3 y	Duration >10 y	Site-scale	Broader scale
LEMS	98	60	56	61	7	86	12
HEMS	27	33	81	63	11	74	19
General mixed species	13	62	31	54	38	62	38
Mountain ash	122	61	48	59	22	75	20
Alpine ash	46	76	78	52	17	76	17
River red gum	12	58	75	67	17	83	0
Box-ironbark	16	75	75	75	6	63	31
General	4	75	100	0	75	0	25
Total*	292	62	60	61	15	79	15

*Totals are less than arithmetic sums because documents often had more than one entry per column opportunity for immediate peer review than those associated with larger research programs.

The majority of studies spanned three or fewer years (61% of documents; Table 5). This is consistent with a broader survey of forest-use research in Australia (70% of 225 studies; Resource Assessment Commission 1993). In addition, 36% of documents contained data spanning one year or less, indicating no seasonal replication; this was particularly prevalent in studies of 'Diversity' and 'Soil' (Fig. 1). The exception was studies relevant to 'Water', where 40% of documents contained data spanning more than 10 y, and a further 26% contained data spanning 5–10 y (from Fig. 1). In part, this reflects early commitment to permanent experimental catchments in Victoria. For example, Melbourne Water's hydrology program, involving the establishment of a series of catchment experiments in the Central Highlands from the 1950s to 1970s (O'Shaughnessy and Jayasuriya 1991), has provided long-term, rigorous data that are relevant to contemporary issues and form the basis for recent research programs (e.g. Vertessy *et al.* 1998).

The greater duration of water-related studies is consistent with national data, and has been partly attributed to lesser effort involved in automated water sampling than, for example, labour-intensive animal surveys (Resource Assessment Commission 1993). Short studies are also symptomatic of funding allocations to research, which have largely been on an 'ad-hoc year-to-year basis' (Lindenmayer 2003). Consequences are a limited capacity to detect long-term effects of harvesting, which may be obscured by time lags (Magnuson 1990), and a pronounced difference between the duration of research and the time scales relevant to many management questions in forestry (e.g. nominal rotations for wood production of 80–120 y).

Analogous to restricted time-spans is the prevalence of research at the scale of individual sites (79% of documents; Table 5). This is consistent with a traditional focus of 'silvicultural' research on stand-level effects (Bauhus 1999). It is also a reflection both of the obvious scale of harvesting disturbance (i.e. individual coupes) and of the perceived scale of relevance for some response variables (e.g. localised soil compaction; locally endemic flora). For example, most studies of harvesting effects on 'water' variables (listed in Table 4) have been at the scales of catchment and region (27 of 35 documents), reflecting mobility of water in the landscape and related scales of management. However, other mobile elements have most often been examined at the scale of individual sites (e.g. 47 of 59 documents relevant to 'vertebrate abundance and behaviour'). Furthermore, effects of harvesting practices on landscape-level variables such as 'connectivity' have rarely been examined (total of 9 documents). Continued dominance of site-scale research is increasingly at odds with the broader spatial context required to manage the diverse criteria for sustainable forest management within Australia (Bauhus 1999) and elsewhere (Aber *et al.* 2000).

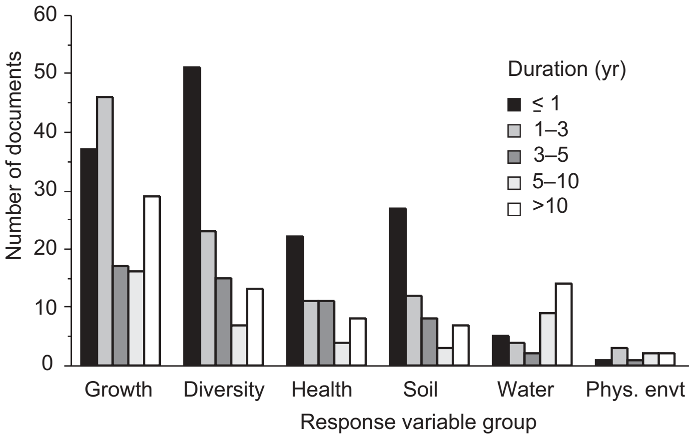

Figure 1. Time-span of data in core documents relevant to each group of response variables. Total numbers per group were less than in Table 7 because duration was not relevant to all documents.

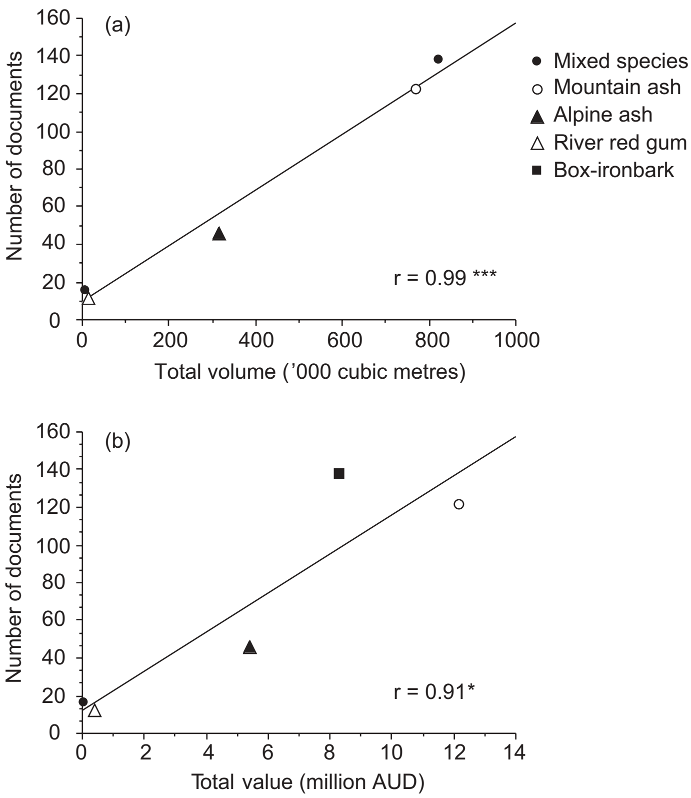

Figure 2. Correlation between the number of core documents relevant to each forest type and (a) the total volume and (b) total value of sawlogs and residual logs harvested in 2000/01 (data from Table 2). 'Mixed species' includes LEMS, HEMS, and General mixed species (Table 1) because separate volume and value data were not available. '*r*' is the coefficient of correlation between two variables (* = $P < 0.05$; *** = $P < 0.001$).

Forest types and harvesting practices

The number of core documents by forest type was strongly correlated with the volume of timber extracted in 2000/2001 (Fig. 2(a)) and, to a lesser degree, with the value of timber extracted (Fig. 2(b)). This suggests that most research is driven by operational needs and opportunities — that is, greater harvesting activity in a forest type generates more questions regarding environmental impact, and creates more opportunities for investigation. Thus, there were 122 documents relating to mountain ash forest, 98 to LEMS forest, and comparatively few to alpine

Table 6. Numbers of documents that contain research on ecological effects of harvesting practices within each forest type. Harvesting practices are in decreasing order by total number of documents. Bold values indicate current practices in each of the six main forest types (from Table 3).

Harvesting practice	Forest type								Total*
	LEMS	HEMS	General mixed species	Mountain ash	Alpine ash	River red gum	Box-ironbark	General	
Clearfell	**61**	**19**	10	**86**	**29**	1	0	3	179
General	10	8	1	25	20	9	12	1	66
Seedtree	**28**	**13**	0	**13**	**3**	1	0	0	50
Commercial thinning	**14**	**2**	3	**19**	**4**	**0**	**3**	0	39
Shelterwood	**18**	**1**	1	17	7	0	0	0	39
Group selection	**12**	2	1	18	2	0	2	0	34
Non-comm. thinning	5	0	1	3	2	2	5	0	17
Single tree selection	**6**	**0**	0	1	1	**0**	**0**	0	8
Retained overwood	2	1	0	4	1	0	0	0	7
Clearfell modified	1	0	0	2	0	0	0	0	3
Coppice with standards	0	0	0	0	0	0	**1**	0	1
Total *	98	27	13	122	46	12	16	4	292

*Totals are less than arithmetic sums because documents often had more than one entry per row or column

ash forest (46), HEMS forest (27), box-ironbark forest (16), and river red gum forest (12; Table 6).

Most research has focused on Clearfell harvesting (179 documents; Table 6) despite its application to a smaller area than Seedtree, Single tree selection and Commercial thinning practices (Table 3). This apparently disproportionate interest in Clearfell harvesting could be due to its controversial reputation here and elsewhere (Keenan and Kimmins 1993). It also reflects the dominance of Clearfell harvesting in mountain ash and alpine ash forests (Table 3). These high-yielding forests are mostly located near population centres and, in addition to wood production, are valued for water catchment, recreation, and flora and fauna conservation (Attiwill and Fewings 2001). Less emphasis has been placed on the effects of Seedtree harvesting (50 documents), possibly reflecting its classification as an even-aged practice (Squire *et al.* 1991; Department of Sustainability and Environment 2003) with similarities to Clearfell harvesting.

At the other end of the harvesting continuum, there has been little focus on Single tree selection (8 documents; Table 6) despite its use over large areas in river red gum forest (Table 3). Here, as in box-ironbark forest, effects of harvesting have been mostly evaluated in 'general' terms, without specification of particular practices (9 and 12 documents; Table 6). Effects of other management issues have tended to overshadow those of recent harvesting practices, including changed flooding regimes in river red gum forest (e.g. Dexter *et al.* 1986), and intensive historical clearing and harvesting in box-ironbark forest (e.g. Traill 1993). Alternatively, Single tree selection could be viewed as relatively low impact since harvesting is more dispersed and, in river red gum forest, is not usually followed by site preparation or regeneration practices (Di Stefano 2002). However, basic questions remain. These include its effects on tree regeneration and on the abundance and continuity of habitat trees (Bauhus 1999; Di Stefano 2002). In box-ironbark forest, where the area available for commercial harvesting has now been substantially reduced (Environment Conservation Council 2001), limited evaluation of specific harvesting practices will hinder predictions of the impacts of proposed restorative practices in National Parks such as 'ecological thinning'.

More harvesting practices have been examined in those forest types with the greatest number of core documents. Thus, 10 practices have been examined in each of mountain ash and LEMS forest, 5 in box-ironbark forest, and 4 in river red gum forest (Table 6). Some research has been conducted on the ecological effects of non-standard, 'potentially-available' practices (e.g. Department of Natural Resources and Environment 1998, 2001) in mountain ash (4 documents on Retained overwood and 2 on Clearfell modified) and LEMS forests (12 on Group selection; Table 6). Not surprisingly, there are no data on which to base ecological assessments of alternative practices in river red gum forest (e.g. Group selection; Di Stefano 2002).

Biological response variables

The numbers of core documents relevant to response variable groups decreased in the order: Growth > Diversity > Health > Soil > Water > Physical environment (Table 7). Overall, 'Tree regeneration' was the most frequently examined response variable (87 documents), followed by Tree growth (83), Vegetation structure (69) and Vertebrate abundance and behaviour (59). Relative quantities within groups are indicated in Table 4. Tree regeneration and Tree growth were the sole or predominant variables in each decade from the 1930s to the 1990s (data not shown). This reflects the traditional primacy of wood production objectives in harvested forests (Florence 1997). However, while

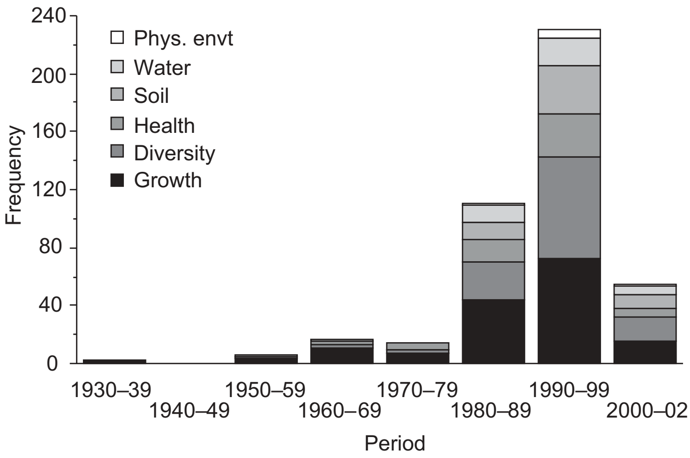

Figure 3. Frequency of examination of effects of harvesting practices on groups of response variables by period of document release. Cumulative frequencies are greater than the total number of documents for each period because many documents contain examinations of more than one response variable.

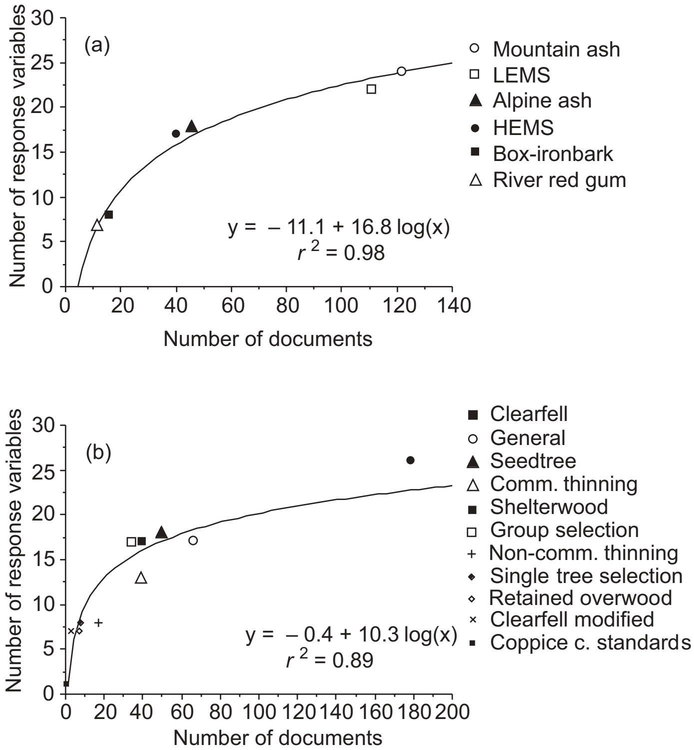

Figure 4. Relationship between number of core documents and number of response variables examined for (a) forest types and (b) harvesting practices. In (a), 'General mixed species' forest is included in both LEMS and HEMS forests.

tree regeneration and growth were of enduring concern, the variety and frequency of examination of other response variables increased in the 1980s and 1990s (Fig. 3). For example, 'Diversity' was rarely examined before 1980 but was examined as frequently as 'Growth' in the 1990s and from 2000 to 2002 (Fig. 3). This trend reflects a worldwide expansion in social values for forests (Aber *et al.* 2000) and, consequently, an increased demand for knowledge relating to both traditional wood-production objectives and diverse non-wood objectives (Florence 1997; Franklin *et al.* 1997; Perry 1998; Bauhus 1999).

While the variety of research increased, many response variables remained under-examined. Effects of harvesting practices on the soil, water and physical environment have not been examined in river red gum and box-ironbark forests, and only rarely examined (0–5 documents) in HEMS and alpine ash forests (Table 7). This accords with relatively low levels of research activity in these forest types, and contrasts with the greater variety and frequency of examination of variables in mountain ash and LEMS forests (Table 7; Fig. 4(a)). Also in accordance with research activity, there has been a greater range of response variables examined after Clearfell harvesting (26 variables) relative to, for example, Single tree selection (8) and Coppice with standards (1; Fig. 4 (b)).

Document numbers by response variable and harvesting practices within each forest type (data not shown) indicate the following:

- The greatest range of response variables has been examined after Clearfell harvesting in each of LEMS, HEMS, mountain ash and alpine ash forests.

Table 7. Numbers of documents that contain research on effects of harvesting practices on groups of response variables within each forest type

Forest type	Response variable group						Total*
	Growth	Diversity	Health	Soil	Water	Physical environment	
LEMS	48	43	23	19	10	2	98
HEMS	16	13	5	1	5	1	27
General mixed species	5	2	1	5	7	0	13
Mountain ash	59	53	26	31	19	7	122
Alpine ash	22	21	7	4	4	0	46
River red gum	6	5	2	0	0	0	12
Box-ironbark	9	9	1	0	0	0	16
General	3	1	1	0	1	0	4
Total*	154	117	59	57	35	9	292

*Totals are less than arithmetic sums because documents often had more than one entry per row or column

- Comparatively less research, covering a narrower range of response variables, has examined effects of Seedtree harvesting despite its extensive application in LEMS and HEMS forests.
- Effects of harvesting practices other than Clearfell on soil, water and the physical environment have rarely been examined in LEMS, HEMS, mountain ash and alpine ash forests (0–6 documents per response variable).
- There has been negligible research on four current harvesting practices in HEMS forests (Shelterwood; Commercial thinning; Single tree selection; Non-commercial thinning) for all response variables (0–2 documents).
- There have been no studies on the effects of harvesting and regeneration practices on Gas emissions and Fire regimes, and fewer than 5 documents contain research on the following response variables: Belowground biomass (2 documents), Total ecosystem biomass (2), Tree physiological processes (2), Invertebrates (4), Plant genetics (2), Vertebrate genetics (1), Introduced fauna (2) and Soil biological (2).

Conclusions

The quantity and diversity of research on the ecological effects of timber harvesting in the native forests of Victoria increased from 1980 and particularly throughout the 1990s. This reflects trends in societal concerns and demands and, together with a strong correlation between quantity of research and current volumes of extracted timber, is an indication of the direction of research to achieve the goals of forest management.

Partly due to the relatively recent surge in research activity, many aspects of timber harvesting effects in Victoria's forests remain under-examined. Based solely on numbers of relevant documents (i.e. not on the quality of research), there has been negligible to minimal research on the ecological effects of harvesting in river red gum and box-ironbark forests, of four current harvesting practices in HEMS forests, and of non-standard practices in most forests. Studies of harvesting effects on the soil, water and physical environment remain scarce in HEMS, alpine ash, river red gum and box-ironbark forests, and are limited for all practices other than Clearfell in mountain ash and LEMS forests. In contrast, traditional interests in tree regeneration and growth are more evenly represented across forest types and harvesting practices.

It can be argued that a lack of detailed knowledge of harvesting effects on all response variables in each forest type is inconsequential since harvesting practices have been designed according to broad ecological principles 'which by their generality subsume the need for detailed information on every population of every species in every stand of forest' (Abbott and Christensen 1994). Indeed, the complexity of native forest ecology and the back-drop of an ever-changing social environment, mean that 'ecological data … will always be incomplete' (Abbott and Christensen 1994). In this context, research on ecological effects of harvesting would be most constructive if studies addressed explicit ecological theories and tested their generality. However, we found a distinct lack of stated research theories and hypotheses (see Bennett and Adams 2004). Instead, most research was seemingly dictated by immediate operational questions at the coupe level and by short-term funding schedules. This was indicated by a high frequency of studies that were not part of a larger research project, that spanned less than three years, and that were at the scale of individual sites (Table 5).

Small-scale studies will continue to be relevant owing to coupe-to-coupe variation in many response variables (e.g. soil erodibility; endemic flora and fauna). However, the broad temporal and spatial horizons of both ecological knowledge and management arenas increasingly demand that individual studies are placed in a larger context. This context is lacking in most of the evaluated documents (Bennett and Adams 2004) yet is readily described. First, existing knowledge in the form of models or theories, as well as testable predictions (research hypotheses) should be clearly stated. These will indicate whether the study is 'exploratory' (designed to explore data and refine theories) or 'confirmatory' (designed to test hypotheses — Tukey 1980; Loehle 1987). Second, sites should be given a geographic context — at the least, latitude and longitude, climatic data, altitude and geology (Downes *et al.* 2002). These data will assist with evaluations of overall site representativeness (see Mackey *et al.* 1988). Third, studies should have an adequate statistical context. This requires adherence to experimental protocols (such as control, replication and randomisation — Johnson 2002), and complete reporting of data (mean, measure of variation (e.g. sample standard deviation) and sample size — Ellison 2001).

Clear statement of the context of individual studies will increase potential for inclusion in broader experimental and sampling frameworks. For example, 'meta-replication' involves the 'replication of *studies* preferably in different years, at different sites, with different methodologies, and by different investigators' (Johnson 2002). Using analysis techniques such as meta-analysis, results from replicated studies can be used to test whether the collective data demonstrate a consistent and ecologically important effect as opposed to a spurious result from a single study (Gurevitch and Hedges 2001; Johnson 2002). Meta-analyses of pre-existing data on harvesting effects in Victorian forests are not possible due to poor reporting of sample statistics and poor experimental designs (Bennett and Adams 2004). However, new study sites and projects can be chosen with meta-replication in mind. These can then supplement existing sites and studies to collectively ensure representation and replication (Johnson 2002).

Our quantification of documents provides an objective picture of research on harvesting effects in Victoria's native forests. There remains considerable scope to include under-examined forest types, harvesting practices and response variables in research programs. A greater frequency of studies that examine more than one response variable, particularly those relevant to soil, water and the physical environment, would increase potential for multi-variate models and associated predictions. Equally, increased commitment to long-term studies is needed to address the mismatch between the duration of research and the time-scales of management and ecological questions. Finally, we argue that small-scale studies should be placed in a broader experimental context. As indicated above, this requires clear presentation of research models, geographic details, experimental design and complete sample statistics. Greater coordination and integration of studies through, for example, meta-replication and meta-analysis, will increase research efficiency and data longevity, and will greatly assist in testing robustness of ecological theories on the effects of harvesting in native forests.

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References

Abbott, I. and Christensen, P. (1994) Application of ecological and evolutionary principles to forest management in Western Australia. *Australian Forestry* **57,** 109–122.

Aber, J., Christensen, N., Fernandez, I., Franklin, J., Hidinger, L., Hunter, M., MacMahon, J., Mladenoff, D., Pastor, J., Perry, D., Slangen, R. and van Miegroet, H. (2000) Applying ecological principles to management of the US National Forests. *Issues in Ecology* **6,** 1–20.

Attiwill, P.M. and Fewings, J.M. (2001) Sustainable management of the mountain ash (*Eucalyptus regnans* F.Muell.) forests in the central highlands, Victoria, Australia. In: Evans, J. (ed.) *The Forests Handbook, Volume 2, Applying Forest Science For Sustainable Management*. Blackwell Science, Oxford, UK, pp. 310–340.

Bartlett, T. and Lugg, A. (1993) Timber. In: Lugg, A., Marsh, P., Bartlett, A. and King, F. (eds) *Statement of Resources, Uses and Values for the East Gippsland Forest Management Area*. Dept of Conservation and Natural Resources, Victoria, Australia, pp. 126–149.

Bauhus, J. (1999) Silvicultural practices in Australian native State Forests — an introduction. *Australian Forestry* **62,** 217–222.

Bennett, L.T. and Adams, M.A. (2004) Assessment of ecological effects due to forest harvesting: approaches and statistical issues. *Journal of Applied Ecology* **41,** 585–598.

Campbell, R.G. (1997) *Evaluation and Development of Sustainable Silvicultural Systems for Multiple-purpose Management of Mountain Ash Forests — Discussion Paper.* VSP Technical Report, No. 28. Centre for Forest Tree Technology, Forests Service, Department of Natural Resources and Environment, Victoria.

Campbell, R.G., Chesterfield, E.A., Craig, F.G., Fagg, P.C., Farrell, P.W., Featherston, G.R., Flinn, D.W., Hopmans, P., Kellas, J.D., Leitch, C.J., Loyn, R.H., Macfarlane, M.A., Pederick, L.A., Squire, R.O., Stewart, H.T.L. and Suckling, G.C. (1984) *Silvicultural and Environmental Aspects of Harvesting Some Major Commercial Eucalypt Forests in Victoria: A Review*. Forests Commission, Victoria.

Chikumbo, O., Spencer, R.D., Turner, B.J. and Davey, S.M. (2001) Planning and monitoring forest sustainability: an Australian perspective. *Australian Forestry* **64,** 1–7.

Commonwealth and Victorian Regional Forest Agreement Steering Committee (1996) *Comprehensive Regional Assessment East Gippsland: Ecological Sustainable Forest Management Report*. Commonwealth and Victorian Regional Forest Agreement Steering Committee, Canberra.

Commonwealth of Australia (1992) *National Forest Policy Statement*. Australian Government Printing Service, Canberra.

Commonwealth of Australia (1998) *A Framework of Regional (Sub-national) Level Criteria and Indicators of Sustainable Forest Management in Australia*. Montreal Process Implementation Group and Dept of Primary Industries and Energy, Canberra.

Dargavel, J. (1995) *Fashioning Australia's Forests*. Oxford University Press, Melbourne.

Davey, S., Hoare, J., Binning, C. and Bright, C. (1997) Assessment of ecologically sustainable forest management for Regional Forest Agreements. In: Bachelard, E.P. and Brown, A.G. (eds) *Preparing for the 21*st *Century.* Proceedings of the 4th Joint Conference of the Institute of Foresters of Australia and the New Zealand Institute of Forestry, Canberra, Australia, pp. 235–246.

Department of Natural Resources and Environment (1996) *Code of Practice: Code of Forest Practices for Timber Production — Revision No. 2*. Department of Natural Resources and Environment, Melbourne.

Department of Natural Resources and Environment (1997) *Prescriptions for the Management of Harvesting and Regeneration in Native Forests: Central Forest Management Area*. Department of Natural Resources and Environment, Victoria.

Department of Natural Resources and Environment (1998) *Forest Management Plan for the Central Highlands*. Department of Natural Resources and Environment, East Melbourne.

Department of Natural Resources and Environment (2001) *Forest Management Plan for the North East*. Department of Natural Resources and Environment, East Melbourne.

Department of Natural Resources and Environment (2002) *Audit of Compliance with the Code of Forest Practices for Timber Production (and Associated Prescriptions) in State Forest of Victoria 2000/01*. State of Victoria, Department of Natural Resources and Environment, East Melbourne.

Department of Sustainability and Environment (2003) *Regeneration and Reforestation Stocking in Victoria's Native State Forests (1993/94 to 1996/97): Even-aged Silviculture*. Forests Service Technical Report, No. 03-1. Department of Sustainability and Environment, East Melbourne.

Dexter, B.D., Rose, H.J. and Davies, N. (1986) River regulation and associated forest management problems in the River Murray red gum forests. *Australian Forestry* **49,** 16–27.

Di Stefano, J. (2002) River red gum (*Eucalyptus camaldulensis*): a review of ecosystem processes, seedling regeneration and silvicultural practice. *Australian Forestry* **65,** 14–22.

Downes, B.J., Barmuta, L.A., Fairweather, P.G., Faith, D.P., Keough, M.J., Lake, P.S., Mapstone, B.D. and Quinn, G.P. (2002) *Monitoring Ecological Impacts: Concepts and Practice in Flowing Waters*. Cambridge University Press, Cambridge.

Ellison, A.M. (2001) Exploratory data analysis and graphic display. In: Scheiner, S.M. and Gurevitch, J. (eds) *Design and Analysis of Ecological Experiments*. Oxford University Press, Oxford, UK, pp. 37–62.

Environment Conservation Council (2001) *Box-ironbark Forests and Woodlands Investigation Final Report*. Environment Conservation Council, Fitzroy, Victoria.

Ferguson, K.V.M. (1934) A preliminary experiment to determine a suitable method of securing natural regeneration from seed on cut-out areas of red ironbark (*Eucalyptus sideroxylon*). *Victorian Forester* **1,** 26–28.

Flinn, D.W. and Bales, J.L. (1990) *Value Adding and Silvicultural Systems Program: Report by the Expert Group and an Associated Sub-committee to the Program Manager on Study Specifications and Research Priorities for the Value Adding Utilisation System Study*. Value Adding and Silvicultural Systems Program, Victoria.

Florence, R.G. (1997) Towards a new silviculture for the native forests. In: Bachelard, E.P. and Brown, A.G. (eds) *Preparing for the 21st Century*. Proceedings of the 4th Joint Conference of the Institute of Foresters of Australia and the New Zealand Institute of Forestry, Canberra, pp. 89–99.

Forest Stewardship Council (2000) *Forest Stewardship Council Principles and Criteria*. Document, No. 1.2. Forest Stewardship Council, Oaxaca, Mexico.

Franklin, J.F., Berg, D.R., Thornburg, D.A. and Tappeiner, J.C. (1997) Alternative silvicultural approaches to timber harvesting: variable retention harvest systems. In: Kohm, K.A. and Franklin, J.F. (eds) *Creating a Forestry for the 21st Century: the Science of Ecosystem Management*. Island Press, Washington DC, USA, pp. 111–139.

Gurevitch, J. and Hedges, L.V. (2001) Meta-analysis: combining the results of independent experiments. In: Scheiner, S.M. and Gurevitch, J. (eds) *Design and Analysis of Ecological Experiments*. Oxford University Press, Oxford, pp. 347–369.

Hilborn, R. and Ludwig, D. (1993) The limits of applied ecological research. *Ecological Applications* **3,** 550–552.

Incoll, R., Lindenmayer, D.B., Mackey, B.G., Gill, A.M., McCarthy, M.A. and Mullen, I.C. (1997) *Montane Ash and Associated Cool Temperate Rainforest Environments in South-east Australia: A Bibliography*. Working paper, No. 1997/3. Centre for Resource and Environmental Studies, Canberra.

Johnson, D.H. (2002) The importance of replication in wildlife research. *Journal of Wildlife Management* **66,** 919–932.

Keenan, R.J. and Kimmins, J.P. (1993) The ecological effects of clear-cutting. *Environmental Reviews* **1,** 121–144.

King, M., Vale, K. and Dignan, P. (1994) *Ecology, Silviculture, and Management of Victoria's* Eucalyptus regnans *Dominated Ecosystems: A Bibliography*. VSP Technical Report, No. 24. Department of Conservation and Natural Resources, East Melbourne.

Kohm, K.A. and Franklin, J.F. (1997) *Creating a Forestry for the 21st Century: The Science of Ecosystem Management*. Island Press, Washington DC, USA.

Land Conservation Council (1985) *Report on the East Gippsland Area: Review*. Land Conservation Council, Melbourne.

Lindenmayer, D.B. (2003) Integrating wildlife conservation and wood production in Victorian montane ash forests. In: Lindenmayer, D.B. and Franklin, J.F. (eds) *Towards Forest Sustainability*. CSIRO Publishing, Collingwood, Victoria, pp. 47–72.

Loehle, C.J. (1987) Hypothesis testing in ecology: psychological aspects and the importance of theory maturation. *Quaterly Review of Biology* **62,** 397–409.

Lutze, M. and Geary, P. (1998) *Site Preparation*. Native Forest Silviculture Guideline, No. 6. Department of Natural Resources and Environment, East Melbourne.

Lutze, M.T., Campbell, R.G. and Fagg, P.C. (1999) Development of silviculture in the native State forests of Victoria. *Australian Forestry* **62,** 236–244.

Mackey, B.G., Nix, H.A., Hutchinson, M.F., McMahon, J.F. and Fleming, P.M. (1988) Assessing the representativeness of places for conservation reservation and heritage listing. *Environmental Management* **12,** 501–514.

Magnuson, J.J. (1990) Long-term ecological research and the invisible present: uncovering the processes hidden because they occur slowly or because effects lag years behind causes. *BioScience* **40,** 495–501.

Murphy, S., Polak Scowcroft, C. and Coy, R. (1998) *Compendium of Forest Research in Victoria: Published, Unpublished, and Research in Progress*. Bureau of Resource Sciences, Canberra.

O'Shaughnessy, P.J. and Jayasuriya, M.D.A. (1991) *Water Supply Catchment Hydrology Research: Status Report 1991*. Melbourne Water, Melbourne.

Ough, K. and Murphy, A. (1998) *Understorey Islands: A Method of Protecting Understorey Flora During Clearfelling Operations*. VSP Internal Report, No. 29. Department of Natural Resources and Environment, Victoria.

Perry, D.A. (1998) The scientific basis of forestry. *Annual Review of Ecology and Systematics* **29,** 435–466.

Raison, R.J., McCormack, R.J., Cork, S.J., Ryan, P.J. and McKenzie, N.J. (1997) Scientific issues in the assessment of ecologically sustainable forest management, with special reference to the use of indicators. In: Bachelard, E.P. and Brown, A.G. (eds) *Preparing for the 21st Century.* Proceedings of the 4th Joint Conference of the Institute of Foresters of Australia and the New Zealand Institute of Forestry, Canberra, pp. 229–234.

Resource Assessment Commission (1993) *Ecological Impacts of Forest Use: A Survey of Completed Research.* RAC Research Paper, No. 9. Australian Government Publishing Service, Canberra.

Ryan, M.F. (1997) *Silviculture Guideline for the Mixed Species Forests of the North-east Area*. North-Eastern Mixed Species Silviculture Project Report, No. 6. Department of Natural Resources and Environment, Benalla.

Sebire, I. and Fagg, P. (1997) *Thinning of Mixed Species Regrowth*. Native Forest Silviculture Guideline, No. 14. Department of Natural Resources and Environment, Victoria.

Squire, R.O., Dexter, B.D., Eddy, A.R., Fagg, P.C. and Campbell, R.G. (1991) *Regeneration Silviculture for Victoria's Eucalypt Forests*. SSP Technical Report, No. 6. Natural Resource Systems Division, Department of Conservation and Environment, Victoria.

Standards Australia (2002) Forest management — economic, social, environmental and cultural criteria and requirements for wood production (The Australian Forestry Standard). Pre-publication final committee draft. Australian Forestry Standard Steering Committee and Technical Reference Committee, Canberra.

Traill, B.J. (1993) Forestry, birds, mammals and management in box and ironbark forests. *Victorian Naturalist* **110,** 11–14.

Tukey, J.W. (1980) We need both exploratory and confirmatory. *American Statistician* **34,** 23–25.

Vertessy, R.A., Watson, F., O'Sullivan, S.K., Davis, S., Campbell, R., Benyon, R.G. and Haydon, S.R. (1998) *Predicting Water Yield from Mountain Ash Catchments*. Industry Report, No. 98/4. Cooperative Research Centre for Catchment Hydrology, Clayton, Victoria.

Woodgate, P.W., Peel, W.D., Ritman, K.T., Coram, J.E., Brady, A., Rule, A.J. and Banks, J.C.G. (1994) *A Study of the Old-growth Forests of East Gippsland*. Department of Conservation and Natural Resources, Victoria.