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Creation of a fire history database for southwestern Australia: giving old maps new life in a Geographic Information System

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ABSTRACT

Land management in fire-prone regions must consider the impacts of fire on organisms, habitats and human societies. Maintenance of accurate fire records is an essential tool to enable managers to consider these impacts. Forests in southwestern Australia have a long history of prescribed burning for a variety of land management objectives. Records of fire occurrence for prescribed burns and wildfires have been maintained since 1937 as microfiche images of paper maps. In this paper, we describe the process used to convert these old maps, as well as more recent spatial data, into one spatial database contained within a Geographic Information System. This methodology has broad interest to those who maintain similar spatial information. This fire history database (FHD) contains both spatial and non-spatial (descriptive) information on prescribed burns and wildfires, including perimeter, area, season-of-burn and ignition method. The FHD allows spatial and temporal analysis of fire history, and we present some regional trends of fire history for the Warren Region. Prescribed burns dominate the fire history, though the occurrence of large wildfires in 2003 significantly influences the fuel age distribution. In this paper, we describe the functionality and limitations of the dataset, and discuss improvements that can be made to current and future data collection.

Keywords: fire frequency, fire management, fire season, Mediterranean-type ecosystem, prescribed burns, spatio-temporal data, unplanned fire, wildfire

INTRODUCTION

Land management agencies in fire-prone regions are under increasing pressure to manage fire on public lands in an ecologically sustainable way, without endangering societal values and infrastructure. Scientific understanding of the influence of fire on ecological communities is improving fire management and also refining objectives that need to be met by the agencies involved (Le Maitre *et al.* 1993). A greater understanding of the effects of fire frequency, season and intensity on biota is helping to mould paradigms of fire management (Burrows 2008; Gill *et al.* 2002). In addition, the concept of mosaics – creating heterogeneity in the landscape through the use of fire (the 'visible' mosaic; Bradstock *et al.* (2005)) – is influencing landscape management globally (Bradstock *et al.* 2005; Brockett *et al.* 2001; Burrows & Wardell-Johnson 2004; Parr & Andersen 2006). There is also a drive to examine the historical pattern of fire in the landscape (the 'invisible' mosaic; Bradstock *et al.* (2005)), particularly with respect to fire frequency and fire return interval, so that fire regimes can be implemented that benefit the range of organisms and ecological values in a management unit (Burrows 2008; van Wilgen *et al.* 2007).

A critical part of understanding fire regimes is the compilation of databases that bring together all known information on fire history (Morgan *et al.* 2001). Information may be in the form of descriptive data, such as explorers' records of Aboriginal and landscape fire (Abbott 2003; Enright & Thomas 2008; Fensham 1997; Johnson & Marsden-Smedley 2002; Marsden-Smedley 1998) and oral surveys of landowners (Fensham & Fairfax 2003) or Aboriginal communities still connected with country (Burrows *et al.* 2006; Burrows & Christensen 1990). This descriptive data generally has limited spatial accuracy. In contrast, fire history data held by land management agencies is likely to have high spatial accuracy for contemporary periods. Contemporary fire history may be obtained from a variety of sources such as fire records archived by land management agencies (Gill & Moore 1997; Le Maitre *et al.* 1993; McCaw *et al.* 2005; Schmidt *et al.* 2002; van Wilgen *et al.* 2000; Wells *et al.* 2004), aerial photographs (Burrows *et al.* 2006; Sharp & Bowman 2004) and satellite imagery (Allan & Southgate 2002; Gill *et al.* 2000; Kitchin & Reid 1999; Vigilante *et al.* 2004; Yates & Russell-Smith 2003).

In southwest Western Australia, sclerophyllous forests, woodlands and heathlands combine with a mediterranean-type climate to produce an extremely fire-prone landscape (McCaw & Hanstrum 2003). The region is subject to recurrent unplanned fires (wildfires) that result from lightning strikes, accidental ignitions and arson (Underwood *et al.* 1985). The region also experiences one of the longest histories in the world of burning under mild conditions for prescribed land management outcomes (hereafter referred to as prescribed burning). Fire history in southwestern Australia is well documented from around 1937. The Western Australian Department of Environment and Conservation (DEC), and its predecessors, the Department of Conservation and Land Management (CALM) and the Forests Department, have undertaken prescribed burning at a landscape scale for more than five decades. This forest block mosaic has several aims for land management, including strategic fire mitigation (protection of life, property and assets) and conservation of biodiversity (Burrows 2008; McCaw & Burrows 1989). On average, 82% of the annual area burnt in the Warren Region since 1953/54 has been as a result of prescribed fire (Boer *et al.* in press).

Since 1937, the burnt areas in each fire season (usually September – April) were mapped by relevant district offices using colour-codes denoting the fire type (wildfires, silvicultural burns or prescribed burns) and season-of-burn. In 1953/54 the Forests Department took the "momentous" decision to develop a policy of broad-scale prescribed burning in response to escalating unplanned fires that were becoming more difficult to control (Wallace 1966). This policy resulted in more accurate and complete recording of fire occurrence. Prior to 1995, all fire perimeters were captured on paper maps; these were later photographed to microfiche and archived. From 1995 onwards, fire perimeters have been captured electronically into spatial databases, either in raster or vector format. Up until now, these datasets have remained mutually exclusive, with no simple way of determining the fire history of a given point in the landscape.

Early work on digitising DEC/CALM's fire history maps investigated conversion from microfiche into a Geographic Information System (GIS) using subsets of the data. Lang (1997) compiled a fire history database (FHD) for an area of 124 000 ha near Collie in southwestern Australia, and Robertson (1998) compiled a database for 84 000 ha south of Lang's study area. The work described in the current paper drew substantially on their pioneering work. Gill and Moore (1997) provided a comprehensive analysis of contemporary fire regimes in southern Western Australia, drawing on some of the data from Lang (1997) as well as historical fire reports, and recommended that "…immediate attention should be given to the development of a Geographical Information System that includes all spatial fire data from 1937, the date of the first maps." The work described in the current paper is the culmination of this recommendation for the Warren Region, one of three administrative regions of DEC in southern Western Australia. This region comprises over 1 million hectares, and is predominantly a forested region (Fig. 1).

This paper describes the process used to develop the GIS database on fire history records for the Warren Region based on old fire maps and two sources of digital fire records held by DEC. It provides more detail on the methodology of FHD construction than a previous paper that describes the early (non-validated) version of the Warren Region FHD (McCaw *et al.* 2005). This manuscript is to be used as reference material for those wishing to develop a spatial database from known fire records, including information on the georeferencing and digitising procedures, validation, attribute structure, calculation of fire frequencies, and time spent on each step. Further, we provide examples of data output that can be derived from the FHD, such as the annual area burnt by different fire types, frequency distribution of fires, and fuel age characteristics. Finally, we highlight some of the limitations of the FHD, and set out some guidelines for the recording of future fire data that will improve the spatial and temporal record of fire occurrence.

Construction of the fire history database (FHD)

Data sources

The FHD was created from a number of sources held by DEC including: (i) fire history images for the years 1937/38 to 1994/95; (ii) the Forest Management Information System (FMIS), a raster GIS, for the fire seasons 1988/89 to 2004/05; and (iii) vector data for the years 1998/99 to 2004/05. A description of each of the data sources is provided below, and is represented schematically in Fig. 2. The total time taken to put together the FHD was approximately 38 weeks (9 months) (Table 1).

Digital fire history images were created with a high quality scanner (Polaroid SprintScan 35) from microfiche of original maps that showed all wildfires and prescribed burns for each year. The original maps were drawn onto A1 or larger map sheets at scales of 1:50 000 (from 1982/83) and 1:63 360 (prior to 1982/83) at local districts. Although all existing maps were digitised into GIS layers, fire history prior to 1953/54 was excluded from the final FHD because of the poor quality of the maps or fire information as well as the limited coverage across the Region. No maps could be located for some areas in 1958/59 and 1974/75 (approximately one-third of the total area in each case).

FMIS data was available from 1988/89 until 2005 and was captured concurrently with fire history plans until 1994/95. From 1995/96 fire history information was entered directly into the FMIS system and not captured in hard copy. During 1996/97 the cell size of data captured in FMIS changed from 140 m (~2 ha) to 70 m (~0.5 ha). For the years 1988/89 to 1994/95, we used the fire history images rather than the FMIS data because of the greater accuracy and completeness of fire information recorded on the images.

From 1998/99 to 2004/05 vector fire history data was available from various sources within the department, and was no longer recorded on hard-copy maps. This data existed separately to, and was of higher accuracy than, the FMIS fire history data. Much of this data had been captured directly from corporate line work, though some fire boundaries may have been captured from GPS or aerial photography.

The capture of the fire history data involved several stages that are outlined below. The GIS used for the operations was ESRI® software; either ArcView© GIS Version 3.1 or ArcGIS© 9.0 (both ArcView and ArcInfo functionality) depending on the operation being performed. At each step to follow, we have outlined the software used as ArcView 3.1, ArcView 9.0 or ArcInfo 9.0.

Georeferencing

Georeferencing involves transforming the coordinates of an image so that it fits in 'real space' in a specified coordinate system. In this case, the non-georeferenced images were displayed as they had been captured, showing crumpling, folds or tears in the original maps and distortions and misalignment due to microfiche or scanning procedures. CALM Operational Graphics (COG) digital maps were used as reference maps for georeferencing. These maps are produced by DEC, and were in MGA94 projected (Zone50) coordinates. Both the COG maps and the fire history images contain roads, hydrology and cadastral information as well as the Forest Department Grid (FD grid – this is a one mile reference grid). ArcView 3.1 (with the extension Spatial Analyst 1.1) and the freeware program ImageWarp 1.4 were used to georeference images.

Using ImageWarp, a series of Ground Control Points (GCPs) was chosen on each fire history image and the same GCPs chosen on the corresponding COG image or images. A minimum of eight and a maximum of 25 GCPs were chosen on both images to georeference the fire history images. Choosing more GCPs allows for a more complex transformation that may more accurately capture variation in the fire history images. GCPs were preferentially placed near the corners of each image, evenly over each image, and close to fires. Average georeferencing errors (of GCPs) were accepted below 10 m and individual errors below 17 m (the size of individual pixels).

A total of 486 fire history images were georeferenced spanning 1937/38 – 1994/95 which took approximately ten weeks (Table 1).

Digitising

Digitising the fire history images involved tracing around the boundary of fires to create a separate polygon for each fire event ('heads-up' digitising). Shapefiles were created in ArcView 3.1 to capture fires for each district in each year. Fire polygons were captured at between 1:25 000 and 1:50 000 depending on the complexity of fire shapes. Where it was clear that fire boundaries followed roads, cadastral boundaries or hydrology, they were digitised adjacent to these vector layers rather than from the imagery. The fire history was digitised and attributed at a rate of approximately one year per day (i.e. total time spent was approximately ten weeks; Table 1). Digitising errors were within 25 m of overlayed vectors and georeferenced imagery.

An example of considerations for the digitising procedure is presented in Fig. 3. The detail on the map includes: (1) colour shading for different burn types and seasons; (2) the prescribed burn ID or wildfire serial number labelled on the map; and (3) the occurrence of unburnt patches within the prescribed burn. Representation of internal unburnt pockets on the maps was rare. Detail such as this was first recorded in 1955/56, but was recorded (for at least one fire) on only 52 of the 486 map sheets (11%). The 1960s saw the highest proportion of maps showing internal patchiness of at least one fire (34% of map sheets compared to < 10% for all other decades). All internal unburnt patches (as they appeared on the images) were digitised. More typically, however, burns were shaded as the entire land area without internal patchiness ('treated area'). However, some maps contained text that estimated the total area burnt or percentage patchiness, which was recorded in the *Comments* field of the attribute table.

The quality of fire boundaries recorded on the maps was variable, and was largely related to the age of the maps (compare Fig. 3 with Fig. 4). Maps in some parts of the Warren Region prior to 1961 either had no roads or lacked accuracy. As a result, the original maps often had roads hand-drawn to indicate burn boundaries (Fig. 4). Similarly, wildfires were often drawn to the approximate area of occurrence (Fig. 4), and even though this also appears to be the case for more recent years, the person recording the information has contours and other information to more accurately represent the fire boundary (Fig. 3). The misalignment of roads, rivers and subsequently fire boundaries presented problems in the digitising procedure (Fig. 4). These were generally corrected during the validation step to follow the actual alignment of these features.

The main issues encountered during the digitising process were: (1) fires not extending to adjacent images (map sheets) (Fig. 5); (2) fire boundaries not aligning between map sheets; (3) misalignment or complete absence of roads on older maps (Fig. 4); and (4) faded colour-shading on older maps (Fig. 4). These issues were resolved during the validation step.

Attribute structure

Once each fire was digitised, attributes were created for the corresponding record in the attribute table of the shapefile. Fifteen attributes were specified in the FHD (Table 2). Ten of these relate to specific information about the fire (*Year, District, Date, Identifier, Name, Firetype, Season, Ignition, Cause, Burnpurpose*), three relate to measures of area or fire perimeter (*Area, Perimeter, Hectares*), and two provide information about data quality and inconsistencies (*Comments, Confidence*). Attribute values were inferred from the colour-codes on the original maps used to denote *Fire Type*, *Season* or *Burnpurpose*, and from written information stating the *Identifier* (serial numbers for wildfires and burn IDs for prescribed burns), *Ignition Type*, or other *Comments*. Included in the *Comments* field were statements relating to data capture/validation or the quality of information contained in the original maps or FMIS data. Not every record has an entry for each attribute, particularly for earlier years where data were incomplete. In particular, the *Cause, Date* and *Name* of fires contained no entries prior to 2003, and from about 1994 until 2002 there were large gaps in information for *Ignition* (ignition type), *Identifier* (burn or wildfire identification number), *Burnpurpose* and *District*. Fields for *Burnpurpose* were well populated prior to 1984. Attribute information for all FMIS-derived information is limited to *Fire Type* and *Season*.

The main issues that affected attribution of the data were: (1) poorly defined or atypical colour-codes (e.g. the green shading in Fig. 5); and (2) lack of information on the map (particularly the case for older maps where burn IDs or wildfire serial numbers were rarely recorded). There is the possibility of improving the attribution of fires by inspecting fire records held in district offices.

We trialled a means to add further quality to the data by incorporating the attribute field *Confidence* in order to provide an indication of the relative accuracy of fire boundaries. Due to the size of the dataset, we investigated only a subset of the data, concentrating on an area of ~ 40 000 ha for which wildfires were common and roads were poorly mapped prior to the 1960's. Ratings of 'high', 'moderate', 'low' or 'very low' were used to describe the confidence in the accuracy of captured polygons to the fire boundaries they represent on the ground. High and moderate ratings were given to fire boundaries that followed overlay layers closely, and low and very low ratings were given to fire boundaries that deviated significantly from overlay layers or included other anomalies (Table 2). Based on changes to map quality, we anticipated, *a priori*, there to be an increase in confidence ratings following the order of three time periods: 1953–1961, 1962–1971 and 1972–2005. From 1961, roads were drawn into more isolated areas on map sheets. From 1972, there was greater accuracy of topographical and man-made features on map sheets, and from 1982/83 the scale of maps changed from 1:63 360 to 1:50 000 with the introduction of the metric system.

The sums of each confidence rating ('very low', 'low', 'moderate' or 'high') for each time period were calculated, then standardised to be a proportion of the total observations for that time period. The data were fourth-root transformed, and similarities calculated using Euclidean distance. Permutational multivariate ANOVA (PERMANOVA; Anderson (2001)) was performed on the Euclidean distances using the PERMANOVA+ computer program (version 1.0.1, an add-on to the Primer 6 program, version 6.1.11), testing for pair-wise differences between the three time periods, using unrestricted permutation of raw data (9999 permutations). Results are presented in Table 3, and indicate higher confidence ratings for fire boundaries recorded in the most recent period than in the older periods.

Validation

The FHD was validated in two ways. Firstly, we attempted to resolve anomalies that were identified during the digitising process and had been documented in the *Comments* field for each record. Common digitising anomalies included fire boundaries that aligned poorly between adjacent images or were not extended to adjacent images. Secondly, we attempted to resolve differences between the FMIS data and the captured data from the fire history images in each year prior to 1995/96. Cases where the FMIS data existed independently of the fire history data were identified for validation. We consulted fire coordinators in each work centre of the Warren Region to locate supporting evidence about the true boundary of each fire. Supporting evidence included prescribed burn plans, wildfire reports, original fire history maps, Forest Management Plans, aerial photography, recollection of fire events or expert knowledge of the areas in question. Based on district advice most anomalies were resolved by consideration of the most likely boundary (e.g. see Fig. 5). Outlying FMIS data was only captured where significant evidence was available that the fire did occur. *Comments* were recorded for all changes made to the FHD as a result of this validation process.

The fire history vector data from 1998/99 to 2004/05 was thoroughly checked against the FMIS data for the same period. Differences were validated with district fire coordinators, and all changes to the FHD were documented in the *Comments* field.

Approximately eight weeks were spent identifying and correcting anomalies in the FHD and inconsistencies between FMIS and original fire history images (Table 1).

'Integrate' and 'Smooth Line' procedures

When layers for each year of fire history were overlayed, it was evident that small sliver (artificial) polygons existed adjacent to roads and other overlayed vectors (to a distance of 25 m). This was a result of minor errors associated with 'heads up' digitising. To minimise the influence of the artificial polygons on the resultant dataset, two automated snapping procedures were trialled using ArcInfo 9.0: 'Topology' and 'Integrate'. Both methods were partially successful, with the 'Integrate' procedure removing more artificial polygons than 'Topology'. The 'Integrate' procedure snaps polygon nodes from the FHD to the nodes of a given set of overlayed vector layers. Some optimisation of parameters was undertaken to determine which vector layers were best to use for the snapping procedure, the order in which snapping should occur, and the threshold distance that would be used. This optimisation was subjective and systematic. Snap layers were placed in order from most- to least-common fire boundary and snapping thresholds were trialled systematically, finally using a threshold of 25 m. The final layers (themes) used, in priority order were: (1) Sealed roads; (2) Forest blocks; (3) Unsealed roads; and (4) Major hydrography.

Initially, the 'Integrate' procedure was run for all years from 1953/54 to 1994/95 (digitised from the fire history images). After running this procedure, it was found that errors still existed. These were corrected by manually panning over the data in each year at less than 1:25 000 scale, and manually re-aligning nodes where it was considered reasonable to do so (usually to roads or tracks).

FMIS fire history data between 1995/96 and 1997/98 were the only reliable data for this period. Polygons contained jagged edges as they were derived from a raster dataset (70–140 m cells). The ArcInfo 9.0 procedure 'Smooth Line' was used to smooth the boundaries of polygons to more closely match overlayed vectors. To avoid the joining of adjacent polygons, 1 m was subtracted from the boundary of the FMIS data before smoothing. This data was smoothed using the 'PAEK' algorithm with a tolerance of 300 m (500 m for 1995/96). A 'Simplify Line' command using a tolerance of 15 m was then run to reduce the number of nodes. The 'Integrate' procedure was run on the smoothed and simplified data using the same parameters used for the pre-1995/96 data, and errors manually corrected as described previously.

Figure 6 shows how the 'Smooth Line', 'Simplify Line' and 'Integrate' transformations of FMIS-sourced data and manual snapping resulted in the final fire boundary recorded in the FHD.

Compilation of vector data

The attribute structure for each year from 1995/96 to 2004/05 was aligned with the attribute structure used for pre-1995/96 data. All shapefiles (polygons and associated attributes) from 1953/54 to 2004/05 were combined using the 'Merge' command in ArcView 3.1, which appends the features of each theme (year) into a single theme (the final FHD). The output from the compilation of all data sources is a FHD for the Warren region in an ESRI Shapefile format that shows the fire areas as polygons with information attributed to individual fires. The completed FHD for the Warren Region over the period 1953/54 to 2004/05 contains 10 588 fires with a total cumulative area burnt of almost 4.5 million hectares (over a total land area of ~ 1.5 million hectares).

Fire frequency

Fire frequency (the total number of fires) was calculated for the 1972/73 to 2004/05 period because of the greater confidence in the data quality during this period than the preceding period (Table 3). This was achieved by summing all fire events that have occurred at each location with a unique fire history, with polygons less than 0.1 ha deleted. A new field, *Count*, was added to the attribute table for each year and attributed a value of '1' for all records of fire occurrence. The shapefiles for all years were combined using the 'Union' command in ArcInfo 9.0, which retains the full extent and attributes of all years. The resultant dataset has only one polygon for each location, though all fields for all years. All fields were deleted, except the *Count* field denoting the occurrence of a fire for the given year. These values were summed for each record resulting in a value for fire frequency between 1972/73 and 2004/05.

Two days were spent to run the fire frequency procedures. Mapping of this data produces a spatial distribution of the number of fires that have occurred between 1972/73 and 2004/05 (Fig. 7).

The 'Union' command was used to join the fire frequency dataset to the merged FHD. The resultant dataset has multiple polygons and records for each location (unique fire history) with the addition of a value for fire frequency. This constitutes the final FHD (Fig. 2).

DISCUSSION

This paper describes a procedure for digitising fire boundaries drawn on paper maps into a GIS, creating a FHD for the Warren Region of southwestern Australia. As such, this is a methodological paper that may be useful to other agencies with similar data, and provides background for those wanting to use the Warren fire history information for scientific purposes. In the remainder of this paper, we discuss issues that relate to the functionality of the FHD, as well as limitations of the dataset and considerations for capturing fire data in the future.

Development and functionality of the FHD

The main purpose for creating the FHD was to disseminate a Department-wide resource for use in a variety of land management and science-based activities. Of particular importance is the potential use of the FHD in the development of prescribed burning operations. Currently, the Department maintains a database on fuel ages without the supplementary information about fire history. The benefit of this FHD is that it functions as a fuel age database as well as maintaining historical information on all past fires in the region (such as seasons-of-burn and fire type). The FHD then becomes a critical resource in burn planning, which aims to develop burn plans up to three years in advance for a range of land management outcomes, including maintenance of biodiversity and strategic fuels management (Sneeuwjagt 2000). The overlap of past fires allows fire planners to maintain a 'visible' (spatial) mosaic of fuel ages and seasons-of-burn, as well as to develop strategies to maintain the 'invisible' (temporal) mosaic of fire intervals (Bradstock *et al.* 2005). This 'invisible' mosaic is more difficult to conceptualise and manage for, but the majority of fire science suggests that knowledge of both the 'visible' and 'invisible' mosaic has better conservation outcomes (Bradstock *et al.* 2005; Keith *et al.* 2002). The maintenance of good fire history records and ongoing scientific research, combined with active fire management, is an example of adaptive management for the conservation of southwest Australian ecosystems (Burrows & Abbott 2003).

This historical data is probably among the oldest and most accurate records in the world of fire history over a large area. The user can interrogate the FHD based on various attributes by running queries in the GIS. The FHD can be overlaid by other point, vector or raster data such as animal sightings, vegetation maps and remote sensing, and maps can be generated of fire history in relation to these other data layers. This database becomes the first step in an effort to produce an integrated FHD for the entire DEC-managed estate of Western Australia, and follows on from the work of Lang (1997) and Robertson (1998) who pioneered the methodologies used here. Already, this database has been used to investigate the efficacy of prescribed burning to reduce unplanned fire size and number (Boer *et al.* in press), and the influence of contemporary fire regimes on biota and ecosystem processes (McCaw *et al.* 2005; Pekin *et al.* 2009; Wittkuhn & McCaw 2007; Wittkuhn *et al.* 2008; Wittkuhn *et al.* 2009).

Regional patterns in fire history

For the purposes of highlighting the information contained in the FHD, we produced charts showing annual area burnt by fire type (1953–2005), fire frequency (1972–2005), and fuel-age, or year last burnt (1972–2005) for all DEC-managed lands in the Warren Region. In addition to the area within each fuel age category, we fitted the simplest negative exponential model to the fuel age data, which assumes that a fire has an equal probability of occurrence at any fuel age (Johnson & Gutsell 1994). This was performed by obtaining the best fit exponential curve to the fuel age data.

The annual area burnt by fire type shows that there was a general increase from a combined 40 000 ha burnt by wildfires and prescribed burns in 1953/54 to a maximum of around 150 000 ha in 1968/69, then a general decrease to less than 60 000 ha in 2004/05 (Fig. 8).

More than 60% of the DEC estate has been burnt three or four times since 1972/73, with few areas burnt more than six times (Fig. 9). The greatest number of fires that has occurred between 1972/73 and 2004/05 is eight, although this only amounted to 2 ha over the timeframe, and may be a result of errors in data capture. Similarly, < 300 ha has experienced seven fires.

The fuel age distribution for the Warren Region is dominated by around 140 000 ha of land that was last burnt in 2002/03 (Fig. 10). There is also a large area that was last burnt between the years 1993 to 1997, and a small area that was last burnt between the years 1998 to 2001. This difference contrasts with the simplest negative exponential model fitted to the data.

The fire history for the Warren Region is dominated by the occurrence of prescribed burns due to the highly-managed nature of the area (Fig. 8; see also Boer *et al.* (in press)). It is worth noting the significant increase in prescribed burn area from 1961/62 (Fig. 8). In 1961, Western Australia experienced extensive wildfire activity when the town of Dwellingup was destroyed and wildfires burnt throughout the southwest (Wallace 1966). This led to a change in attitude to greater use of prescribed fire to manage fuel loads, and during the 1960s the first use of aircraft to drop incendiaries occurred. Also notable on this graph is the large area burnt in wildfires in 2002/03, which reflected a season of unusually high wildfire activity (CALM 2003). The large area burnt was a result of four years of drought conditions that restricted prescribed burning operations and therefore increased the flammability of fuels (CALM 2003). A series of lightning ignitions in January, February and March 2003 resulted in the occurrence of large wildfires. This pattern is also apparent on the fuel age plot, which shows only small areas last burnt between 1998–2001 (i.e. many were burnt-over in the 2002/03 season; Fig. 10). The contrast of observed fuel ages against the fitted values from a simple negative exponential model shows that they are not easy to fit statistically (Gill & McCarthy 1998; Gill & Moore 1997), especially in years of unusually high wildfire activity such as 2002/03. These issues, including the patterns of historical data in the Warren Region, are investigated in a related paper (Boer *et al.* in press) and so will not be discussed in depth here.

Limitations of the dataset

When digitising fire boundaries, it was assumed that colour-shading on maps was an accurate representation of on-ground extent of the fire. Sources of error in this assumption are: (i) human error when recording boundaries of fires; (ii) inaccurate or poorly-annotated mapsheets available at the time; or (iii) neglecting to record fires (although there is no evidence that this has been the case). In particular, we noted poorly-annotated map sheets that existed up until 1971, and even longer in more isolated (eastern) zones, that lacked road networks, streams or other physical features commonly used in fire mapping (Fig. 4). While this error is critical when known fire histories are required at a point or plot-scale, the data is still useful at larger scales, such as state-wide or region-wide analysis of area burnt (Williams *et al.* 1994).

To identify and document potential errors in the database, we included fields in the attribute table called *Comments* and *Confidence* (Table 2). Both of these were useful to ensure that problems were identified, and in the case of the *Confidence* fields, we could identify three distinct periods that differed in their map quality, and which corresponded reasonably well with our *Confidence* ratings: 1953–1961, 1962–1971 and 1972–2005 (Table 3). These periods were directly related to improvements in map quality which improved the reliability of mapped fire perimeters. Despite improvements in quality of maps and accuracy of recording, in recent times the confidence in recorded boundaries of some fires still remains low (Table 3).

One of the potential errors in the FHD was that edge-burning ('edging': burning away from roads or firebreaks under mild conditions and for the purpose of shoring up a fire edge prior to the main ignition) may not have been recorded. Some edging was recorded on old fire maps (Fig. 4), though this would have been indicative only as the depth varies along the edge (minimum depth prescribed prior to core ignition is 100 m). Edging may be undertaken six to twelve months prior to the core ignition, which results in the edge and the core ignition having different seasons-of-burn. It is likely that much of the edging was not recorded and was incorporated into the core ignition mapping, hence losing the spatial and temporal differentiation in fire season. This could have implications when undertaking retrospective research into the effects of season-of-burn on biota, as the position of research plots may not accurately reflect the true season-of-burn. It also could mean that the 'invisible' mosaic of burn histories recorded in the FHD is coarser than the real mosaic.

A common problem when capturing any spatial fire data is the degree to which internal patchiness of the burn is represented (Edwards *et al.* 1999; Gill *et al.* 2003; Price *et al.* 2003). This is another potential error producing a coarser mosaic of recorded fire history than may actually exist. The attributes *Area* and *Hectares* (Table 2) are likely to over-estimate the actual area burnt in any one fire, as the majority of prescribed burns were recorded as the area 'treated' and wildfires as the area 'contained' (i.e. the entire area within the fire perimeter). Hence, data in Figures 8 and 10 are likely to be over-estimates. While wildfires are likely to burn more completely than prescribed burns (Christensen & Annels 1985), both will generally have a proportion of their area that remains unburnt (Williams *et al.* 1994). Furthermore, the aim of prescribed burns in southwestern Australia is to retain some portion of the area unburnt. Retaining 20–30% unburnt was a typical objective of prescribed burns in the 1980s (Christensen & Annels 1985), though in more recent times, this figure is less arbitrarily defined and is dependent on the specific burn objectives. Gill and Moore (1997) used 70% as an estimate of areas that burnt in prescribed burns for their analysis of southwest fire regimes, though they suspected significant variation around this figure for individual burns. For historical maps, very rarely was any attempt made to map the patchiness of any fires. The higher proportion of maps showing patchiness in the 1960s (34% compared with < 10% for all other decades) may reflect a priority placed on validating the effectiveness of aerial burning which was introduced in 1966/67 (L. McCaw *pers. comm*[1] .).

Current and future data quality considerations

In this section, we concentrate on four main points that we see as important to the collection of fire records, some of which are already being pursued in Western Australia and elsewhere. These four points relate to (i) using remote sensing to capture actual burn areas (i.e. capturing two-dimensional patchiness), (ii) developing technologies to map three-dimensional patchiness, (iii) recording edging or pre-core-ignition fires separate to the core ignition, and (iv) improving the 'completeness' of information pertaining to individual fires. Points (i) to (iii) are interrelated in terms of the technology used to capture the information, and point (iv) contains an operational basis. Each is discussed below.

(i) *Using remote sensing to capture actual burn areas (2-D patchiness).* Some of the issues in relation to remote sensing and mapping fire patchiness have been discussed above. We see remote sensing as having its greatest benefit in terms of fine-scale mapping of actual burnt areas across large scales. In simple terms, this means mapping burnt and unburnt patches in two dimensions. More work is required to determine the accuracy and scale at which remote sensing captures (or does not capture) unburnt patches (Price *et al.* 2003). This will depend on the management scale at which information about patches is required. In the case of managing land for ecological values, the management scale may in fact be determined by the size, orientation and number of unburnt patches that maintain the ecological values in question (e.g. see Bradstock *et al.* (2005)). In essence, research into patch dynamics and the biota they support will determine the critical resolution required for remotely sensed images (Burrows & Wardell-Johnson 2004).

(ii) *Developing technologies to map three-dimensional (3-D) patchiness.* In addition to 2-D patchiness, there is a 3-D component resulting from fire that has ecological and operational significance. This relates to the consumption of fuels from beneath the soil (e.g. roots and peat) to the highest level of vegetation (i.e. canopy). Some may define this as 'fire severity', though this term has varied definitions, and generally refers to "the magnitude of significant negative fire impacts on wildland systems" (Simard 1991: 31). Fire severity may also be measured using a number of indicators (DeBano *et al.* 1998; Lentile *et al.* 2006) which further complicates the use of this term. A fire history database should not be developed to determine how 'negative' a fire has been, but to provide some measure of 'what got burnt'. This measure should be in three dimensions; that is, as a description of fire-effects on all fuel strata.

Three-dimensional patchiness is difficult to conceptualise and represent in a mapping program, and will differ depending on the vegetation and fuel types. Rapid assessment of 3-D patchiness cannot be undertaken on the ground; remote sensing algorithms derived from comprehensive research using ground data are required (Boer *et al.* 2008). Shu *et al.* (2004) have been investigating methods to assess biomass (fuel) consumption using remote sensing in Western Australian ecosystems. The output of this is a 2-D image that shows 'percentage biomass change', which could be interpreted as a surrogate for 3-D patchiness. This work is ongoing, but it is anticipated this imagery will provide an estimate of changes to fuel strata, relative to the vegetation type in which the fire occurs.

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[1] Dr Lachie McCaw, Principal Research Scientist, Science Division, Dept of Environment & Conservation, Manjimup, WA.

(iii) *Recording edging or pre-core-ignition fires separate to the core ignition*. Future data collection would benefit greatly from the accurate recording of edge burning separate to the core-ignition, including the season-of-burn and fire perimeter. This has benefits for two reasons: firstly, the database can be used to show the mosaic of fire seasons in the landscape (edging creates a mosaic of intensity and season within the main forest block burnt); and secondly, it allows a quantitative evaluation of the depth of edging in relation to the objective set out for the burn. This final point has safety considerations at the forefront of conducting prescribed burns, as it allows the controlling officer to determine if the burnt edge is sufficient prior to conducting the core lighting.

(iv) *Improving the 'completeness' of information pertaining to individual fires*. Attributes of all fires should be accurately and completely recorded by the operations personnel. In the FHD described here, several attribute columns in Table 2 contain missing values. However, as data capture has become more formalised in Western Australia, these fields have been populated. For example, the *Cause* of a wildfire (e.g. lightning, deliberate ignition, escape from a prescribed burn), the *Name* of wildfire or prescribed burn, and the *Date* on which wildfires were declared safe or prescribed burns recorded their last activity were not populated prior to 2003. Other fields are sporadically populated throughout the FHD, such as *BurnPurpose* and *Identifier*.

Computerised fire management systems should alleviate any deficiencies in data collection from this point forward. In particular, there is a need to develop seamless systems that capture operational information to feed directly into the FHD. This would provide a link between the spatial information that is contained in the FHD and the traditional non-spatial data such as date of ignition, date of last activity, predicted rates of spread, observed rates of spread, fire danger indices, soil dryness indices, wind activity, burn objectives, and degree of success against the objectives. A linked spatial and non-spatial database containing these data would provide a valuable resource for fire management and research.

SUMMARY AND CONCLUDING REMARKS

This paper has provided a systematic description of the construction of a database on fire history for southwestern Australia, a region of the world for which prescribed burning by land management agencies dominates the fire regime, but also an area of frequent wildfire occurrence. The clear description of steps in this paper would permit other agencies to develop similar databases where historical maps exist.

The database is useful for mapping contemporary fire regimes, planning prescribed burn programs to maintain the 'visible' (spatial) and 'invisible' (temporal) mosaics (*sensu* Bradstock *et al.* 2005), and obtaining underlying information for scientific studies on fire regimes. We have also described some of the weaknesses in the historical data, and discussed ways of using modern techniques, in particular remote sensing, to improve the interpretation of this data. Similarly, remote sensing provides a basis for improving future data collection, along with rigorous data collection on the ground by fire personnel. In particular, we see a need to collect data that improves the resolution of fire information at spatial and temporal scales, as well as descriptive data linked through the attribute table.

With climate change becoming a recognised threat to ecological processes and fire management globally (Cary 2002; Running 2006; Williams *et al.* 2001), maintenance of fire history in a spatial database is paramount to recognise changes and threats and to identify solutions.

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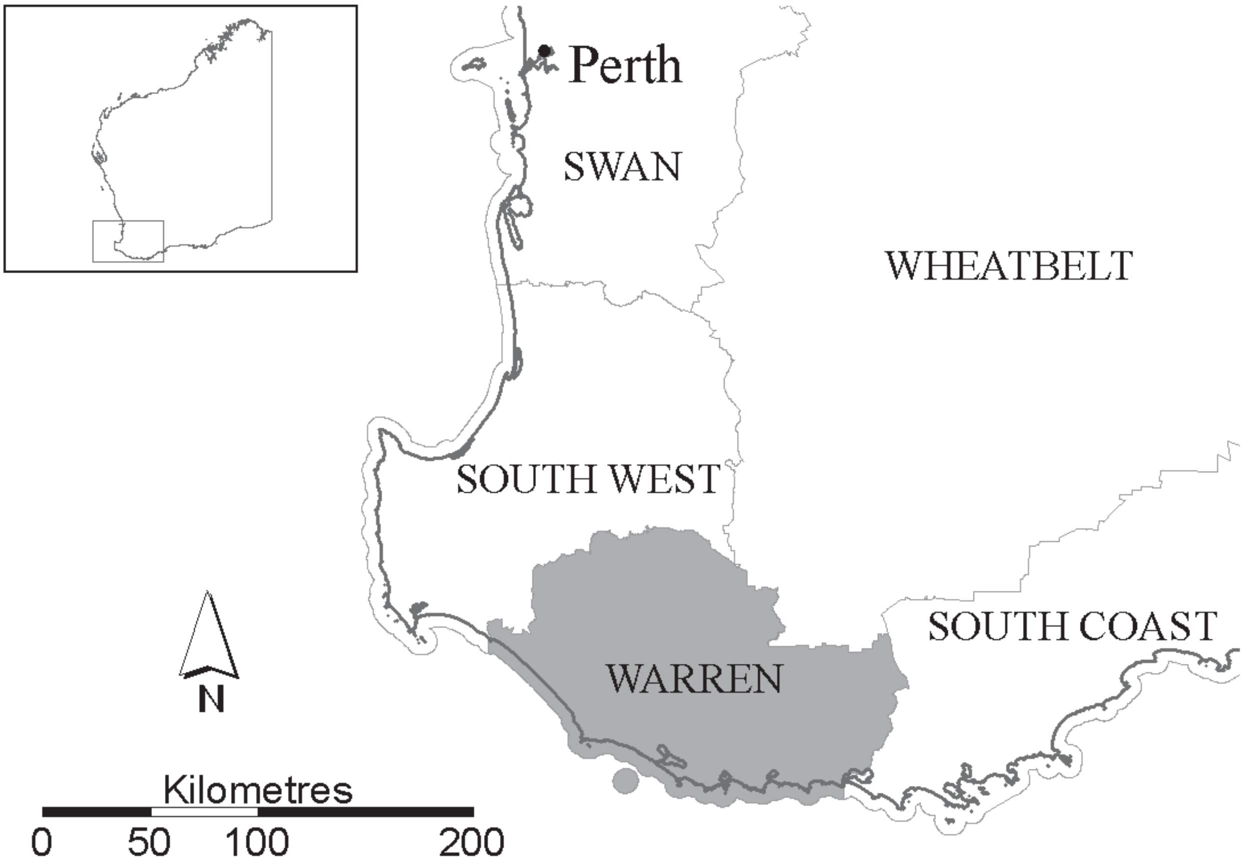

Figure 1. Location of the Warren Region in Western Australia (WA) in relation to the capital city, Perth, and other DEC administrative regions in the southwest of WA.

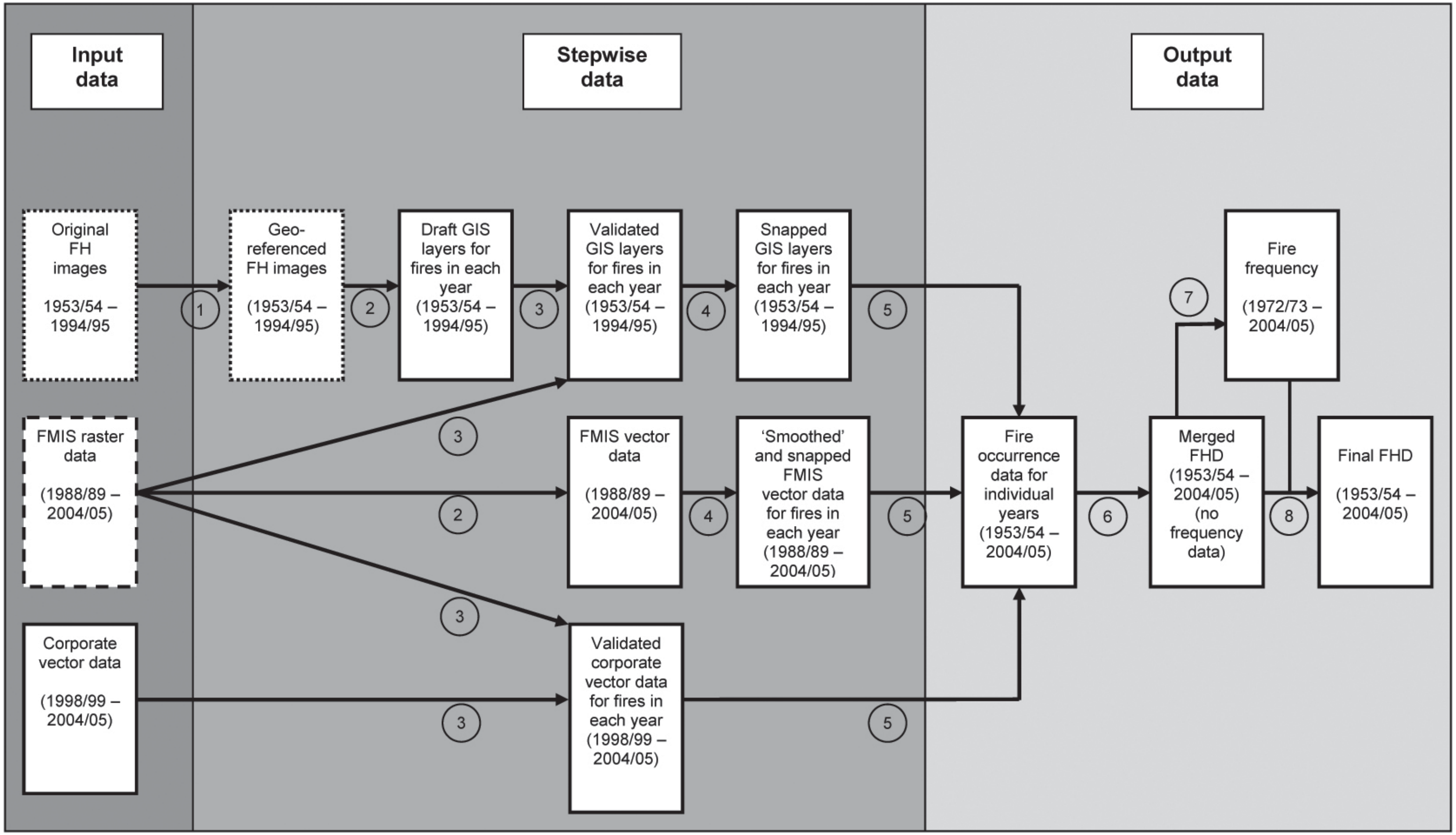

Figure 2. Schematic representation of the steps involved in developing the fire history database (FHD) for Western Australia's Warren region. All vector data is designated by a solid line around boxes, raster data by a broken line, and image data by a dotted line. Explanation of abbreviated terms: FH = fire history; FMIS = Forest Management Information System; GIS = geographic information system. Steps involved in the development of the Warren FHD are as follows: (1) georeferencing of FH images; (2) digitising of FH images and conversion of FMIS into vector format in GIS and attribution of each fire; (3) validation of vector layers for each individual year, and against FMIS raster data; (4) 'Integrate' procedure run on vector layers to snap to GIS layers of roads, forest block boundaries and major hydrology, followed by manual snapping. FMIS vector data was smoothed, before snapping to GIS layers mentioned using 'Integrate'; (5) multiple layers representing fire occurrence for individual years were combined into one database from the three sources of data; (6) layers representing fire occurrence for individual years were merged together into one layer showing all fires through time; (7) calculation of fire frequencies for every polygon in the merged FHD; (8) union of fire frequency column with merged FHD to create the final FHD.

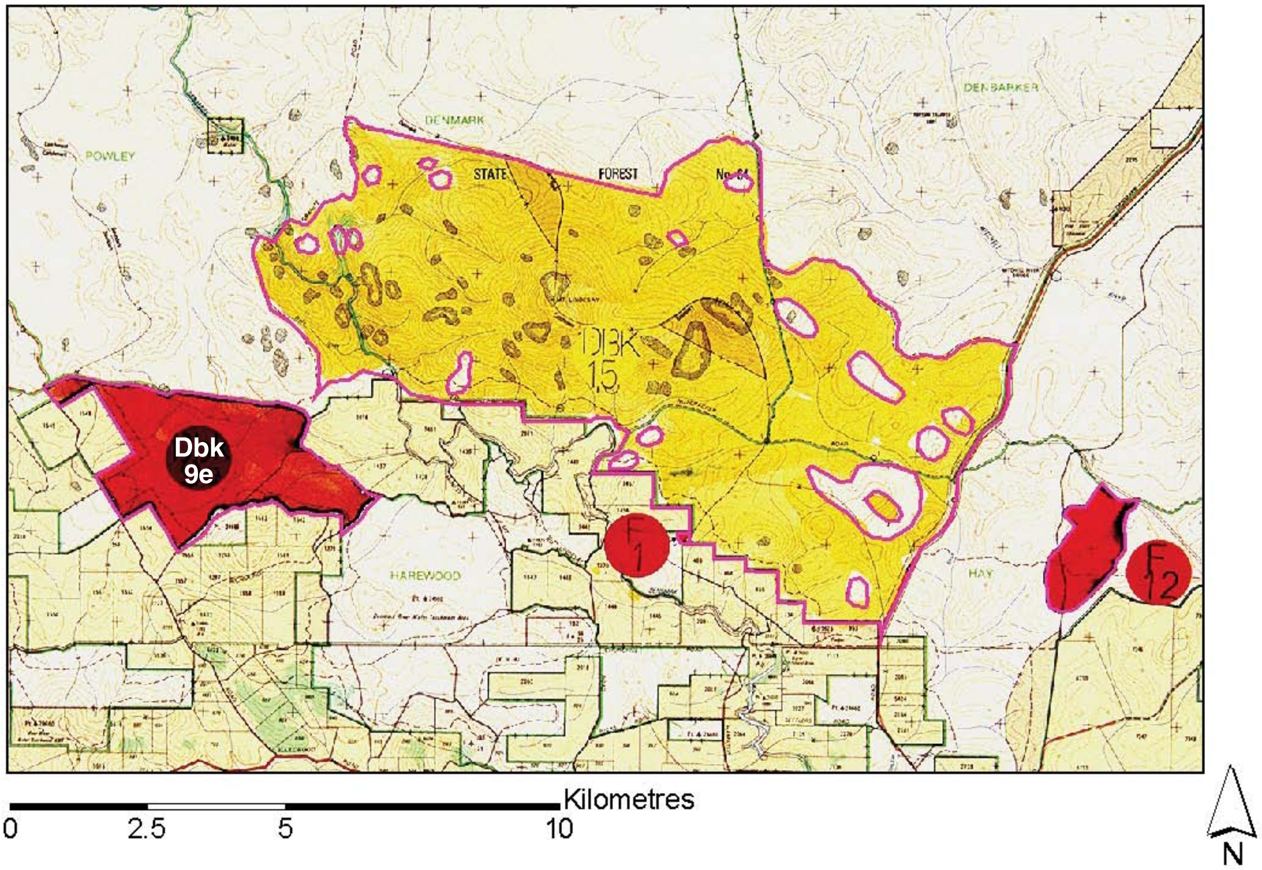

Figure 3. Digitised fires (pink lines) overlaying the original image for fires near Mt Lindesay in 1991/92. Yellow shading denotes a prescribed fire in spring, with the Burn ID 'DBK 15'. Three other fires are shown on the map. Two are wildfires, with wildfire serial numbers 'F1' and 'F12', and one is an autumn prescribed burn, Burn ID 'Dbk 9e' (left hand side of image). Autumn burns were typically shaded brown and wildfires red. On this map, as with many others, it was difficult to distinguish brown from red. This image also contains mapping of unburnt pockets in the spring prescribed burn, possibly from assessment of aerial photographs.

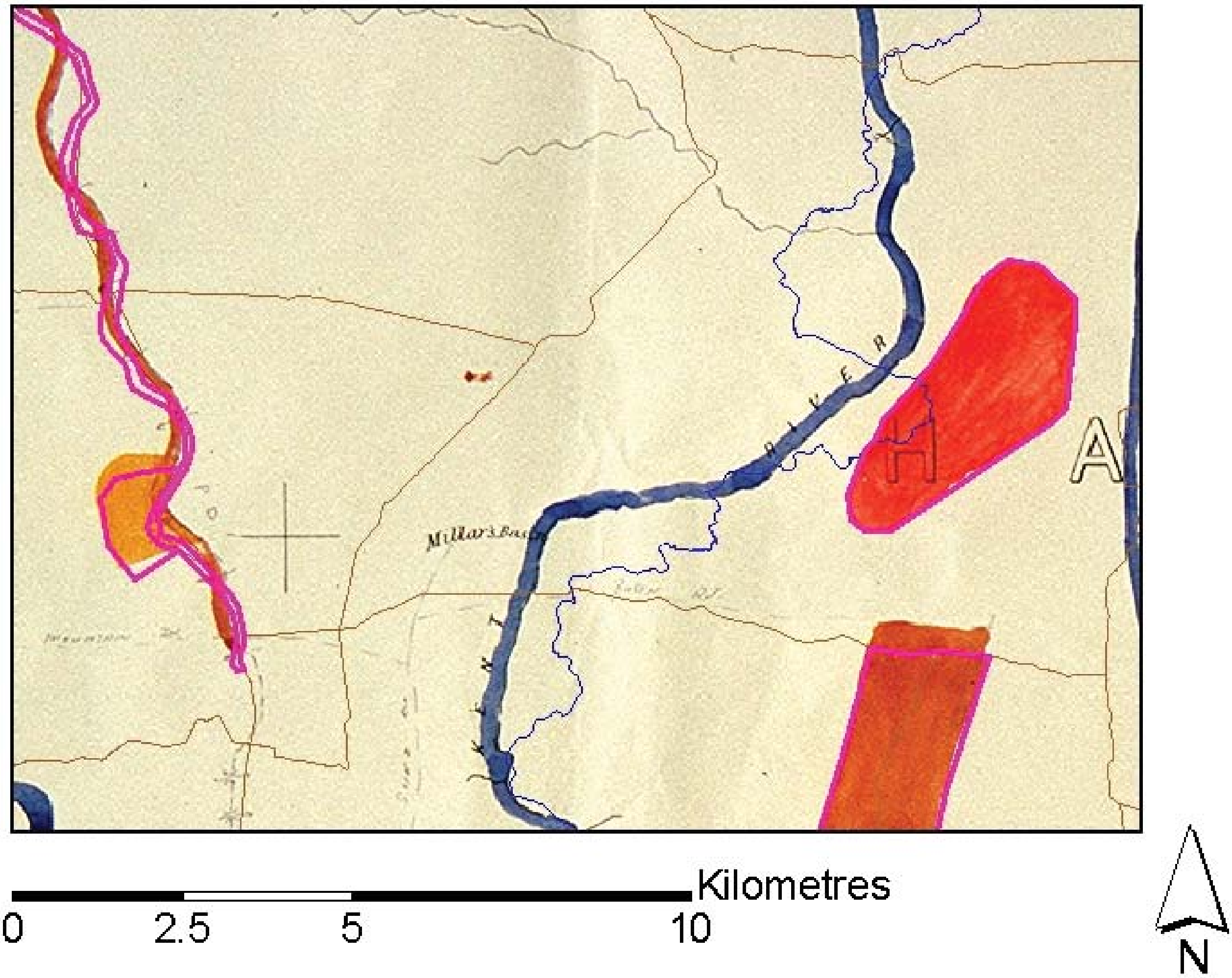

Figure 4. Image of an original fire map from 1957/58 overlain with roads from DEC's corporate data (thin brown lines) and final fire boundaries in the FHD (pink lines). Note the yellow shading (indicating a spring prescribed burn) on the left of the image, including a line of edge-burning (shaded brown), the shape of which has been altered to correspond with the actual road alignment. Brown shading on the bottom right of the image indicates an autumn prescribed burn, and the red shading a wildfire. For some older maps, fading of colours often made it difficult to distinguish red from brown. The northern boundary of the autumn fire has also been altered to follow the road direction. The hand drawn road is barely visible on the map, and often does not match well with actual alignment of roads. Note also the path of the Kent River on the original map and its actual path from the GIS layer (thin blue line). The boundary for the wildfire is particularly arbitrary, given it is not bounded by roads or other physical features. In addition, the recorder obviously had information that it was contained to the east of the Kent River, whereas the actual path of the river puts the wildfire on the western banks, a potential error in the final dataset.

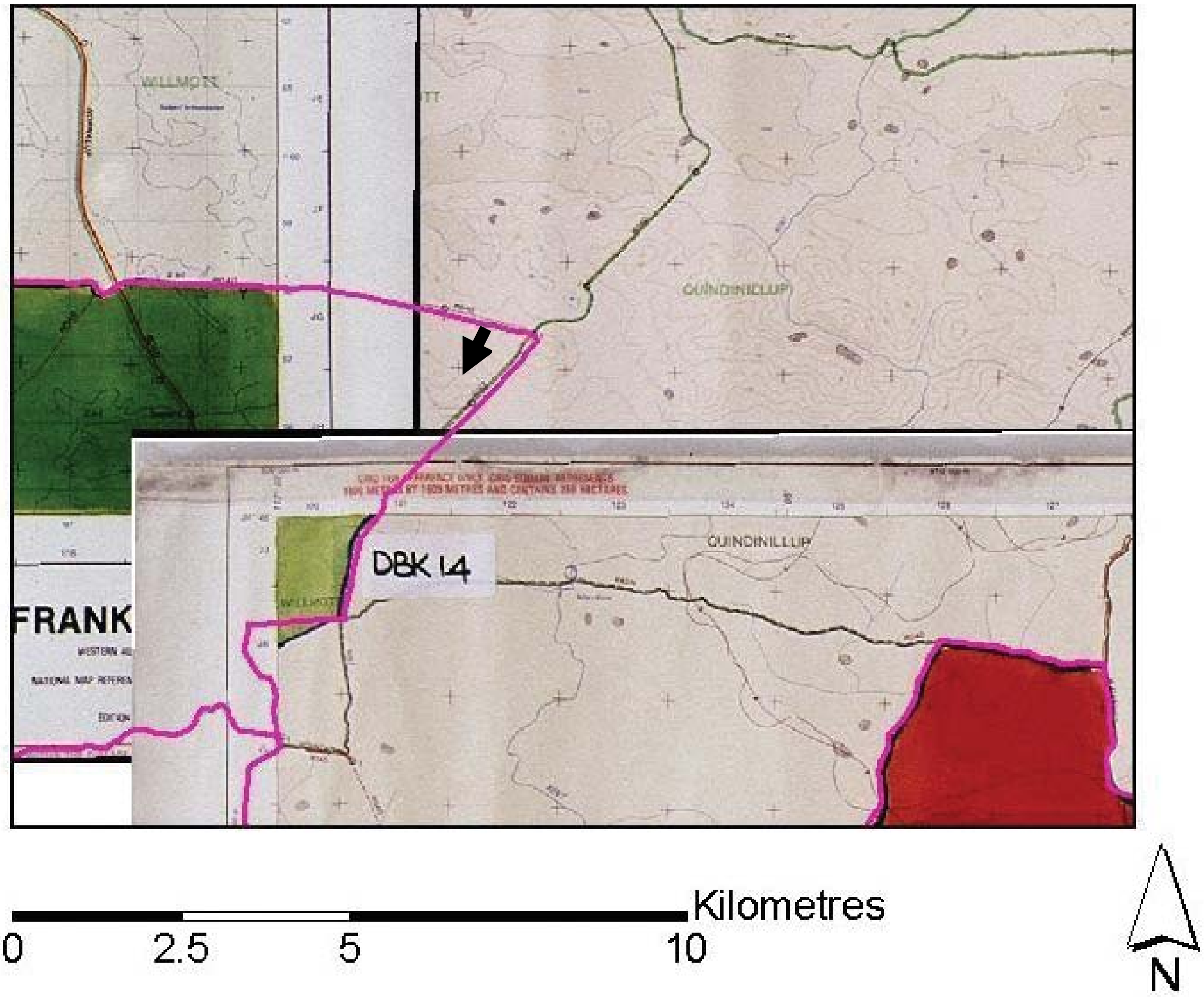

Figure 5. Example of digitising and attribution issues resulting at the junction of three map sheets for fires from 1994/95. The green shading denotes a prescribed fire in spring, which differs from the typical yellow shading on most maps. In addition, the fire has not been shaded for the northeast corner of the burn (indicated by an arrow). Validation with fire coordinators confirmed that this area would have formed part of the burn and the boundary was altered to include this area in the final FHD (pink line).

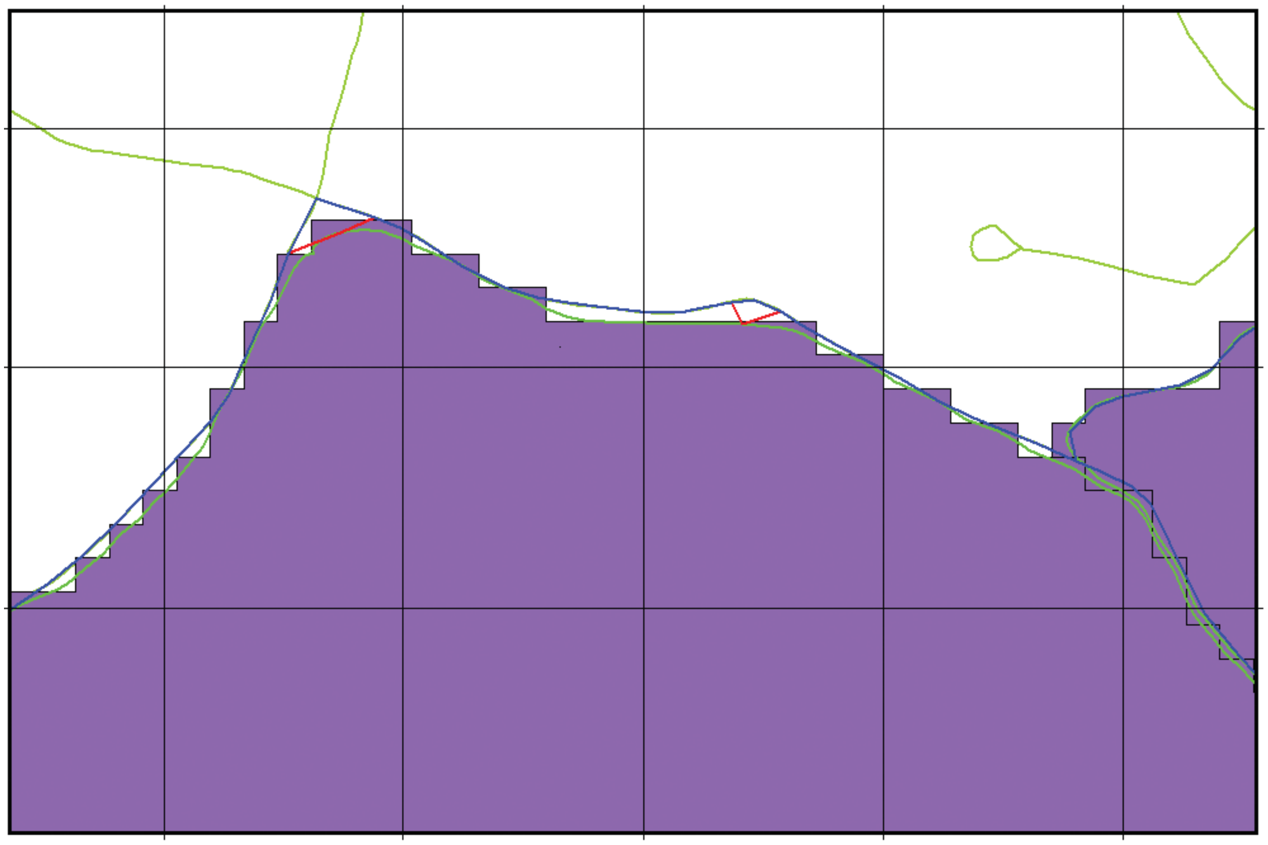

Figure 6. An example of a 'Smooth Line' and 'Integrate' procedure for FMIS (raster-sourced) data to incorporate with vector data for the FHD of the Warren Region, Western Australia. The 'Smooth Line' and 'Simplify Line' transformation of underlying FMIS data (jagged edge purple polygon) produced the green line. An 'Integrate' transformation of the green line produced the red line. The blue line is the result of manual snapping to improve errors and closely follows the overlay layers (roads, forest blocks and rivers). This blue line represents the resultant polygon.

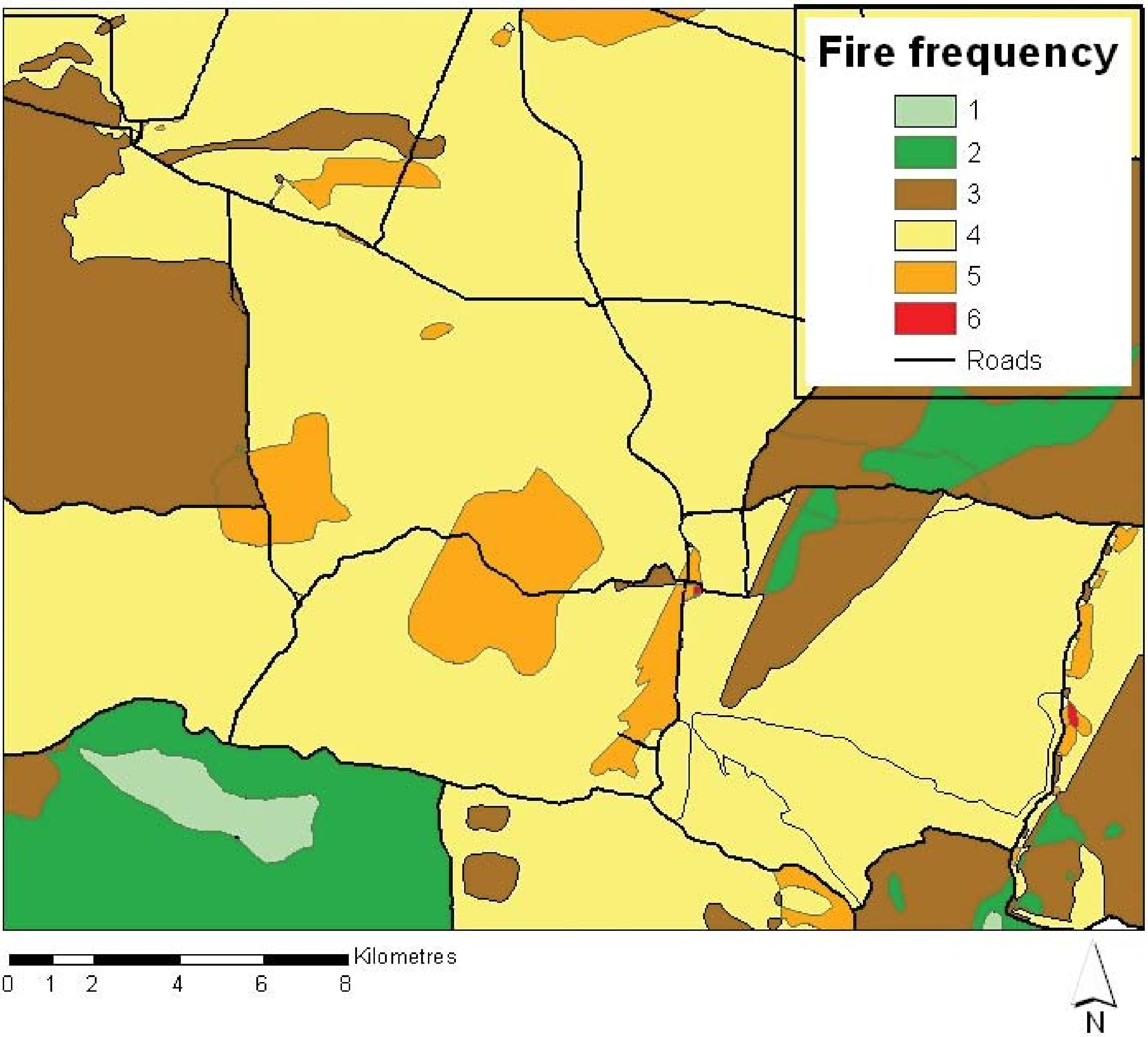

Figure 7. Output from mapping the fire frequency attribute (number of fires between 1972/73 and 2004/05) for an area of ~ 50 000 ha. Light grey lines indicate polygons with unique fire histories in space and time, each of which has been shaded with its fire frequency.

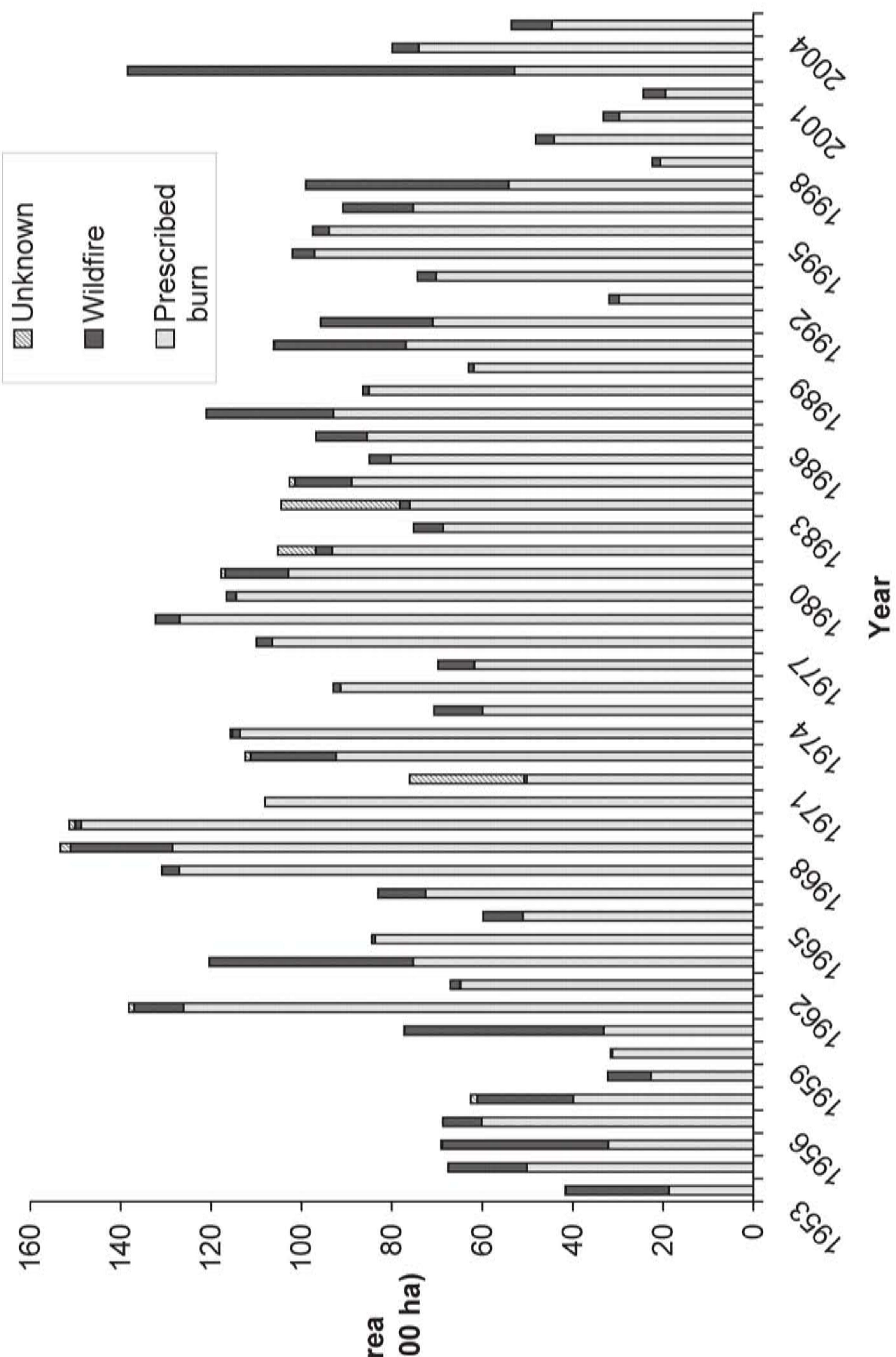

Figure 8. Annual area burnt by fire type (wildfire, prescribed burn, or unknown origin) for the Warren Region of Western Australia, 1953/54–2004/05.

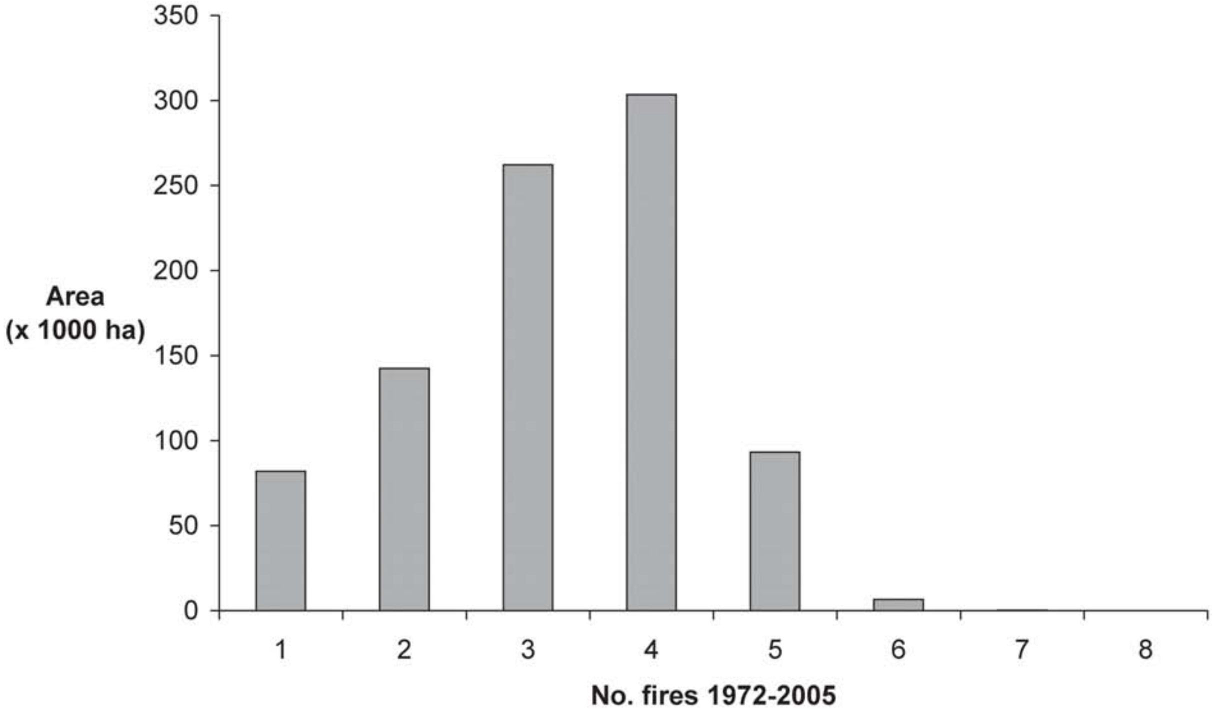

Figure 9. Fire frequency between 1972/73 and 2004/05, graphed as total land area for each frequency class.

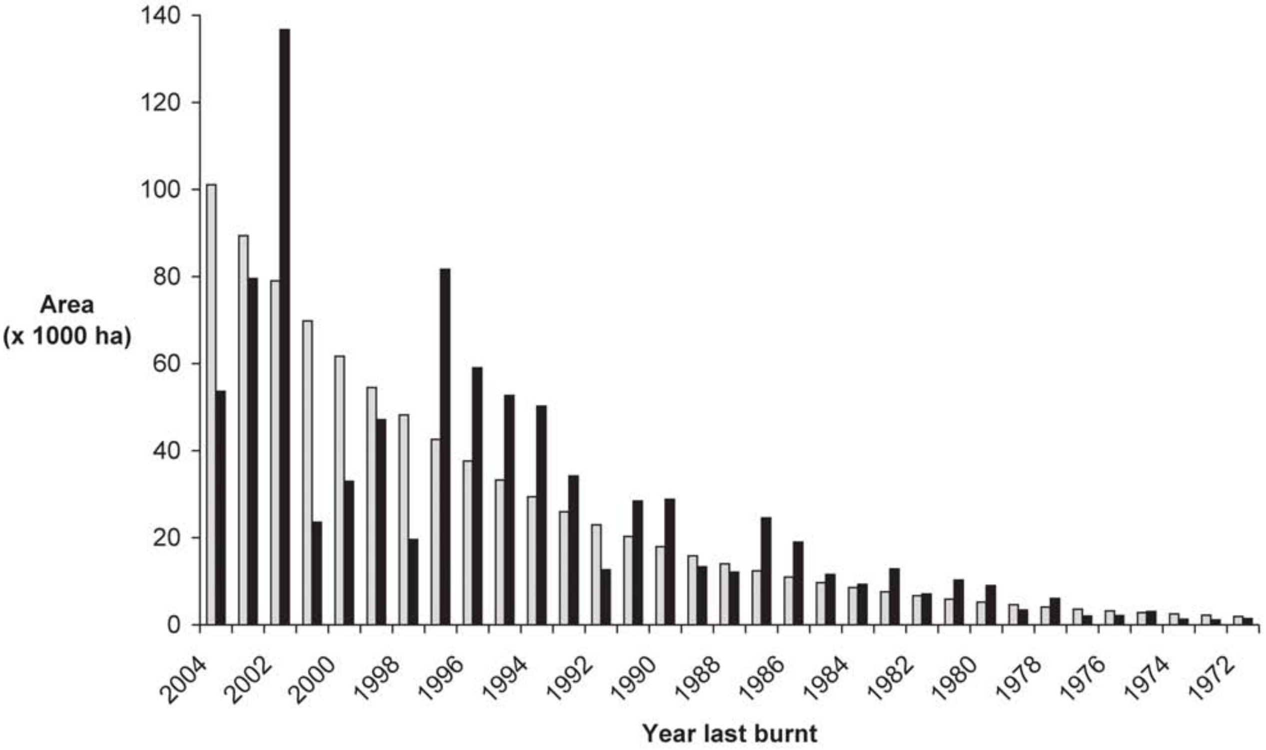

Figure 10. Fuel age distribution for the Warren Region (clipped to DEC-managed estate), showing the total area of land for the year last burnt (black bars) and the simplest negative exponential fitted model to year of last burn (light grey bars).

Table 1

Approximate time spent on each of the tasks associated with constructing the fire history database for the Warren Region in Western Australia.

Task	Weeks
Georeferencing	10
Digitising/attribution	10
Validation	8
Integration	6
Smoothing	4
TOTAL	**38**

Table 2

Attribute structure for the fire history database of the Warren Region, southwest Western Australia.

Attribute	Description	Entries/values	Data type	Data length
Year	Preceding calendar year of each fire season	1953, 1954, …., 2004	Number	4
District	District in which fire was recorded (on fire history maps)	Blackwood, Donnelly, Frankland, Manjimup, Pemberton, Unknown, Walpole. (Note that the current Donnelly district encompasses the old Manjimup and Pemberton districts, and the current Frankland district encompasses the old Walpole district)	Text	30
Date	Prescribed burn last activity date or wildfire detection date	Various	Date	6
Identifier	Prescribed burn ID or wildfire serial number	Various	Text	30
Name	Name of prescribed burn or wildfire	Various	Text	30
Firetype	Type of fire	PB – prescribed burn, WF – wildfire, UN – unknown	Text	2
Season	Season of prescribed burn	AU – autumn, SP – spring, SU – summer, WI – winter, UN – unknown	Text	2
Ignition	Ignition type for a prescribed burn	AC – aircraft, HB – hand burn, HC – helicopter	Text	2
Cause	Cause of a wildfire	Accidental by other industry, accidental by recreational forest users, deliberate, escape from CALM prescribed burn, escape from other burning off, lightning.	Text	50
Burnpurpose	Purpose of a prescribed burn	Advance burn, biodiversity conservation, community/strategic protection, fire research (scientific), hardwood silviculture, hazard reduction (protection), nature conservation, regeneration/slash burn, silvicultural, strategic buffers, tops disposal burn, tourism and recreation, under pine canopy	Text	30
Comments	Comments relating to capture/validation of data and quality of fire history images	Various	Text	80
Confidence	Confidence in accuracy of captured data	High – no uncertainty, Medium – minor uncertainty in boundary or part of boundary, Low – significant uncertainty in boundary, Very Low – major uncertainty in boundary.	Text	10
Area	Area of captured fire (m^2)	Various	Number	16
Perimeter	Perimeter of captured fire (m)	Various	Number	16
Hectares	Area of captured fire (ha)	Various	Number	16

Table 3

(a) Proportion of fires that fell within four confidence levels: ‘high’, ‘moderate’, ‘low’ and ‘very low’ within three specific time periods: ‘1953–61’, ‘1962–71’ and ‘1972–2005’ for a 40 000 ha subset of the data.

(b) Non-parametric PERMANOVA on Euclidean distances (*a priori* pairwise comparison) for confidence levels for the three time periods.

$P < 0.05$ (highlighted in bold) suggests a significant difference between pairs of time periods.

(a)

Time period	High	Confidence level Moderate	Low	Very low	Total
1972-05	0.2	0.5	0.3	0.0	**1.0**
1962-71	0.0	0.2	0.7	0.1	**1.0**
1953-61	0.0	0.3	0.4	0.3	**1.0**

(b)

PAIR-WISE TESTS (9999 permutations)

Pairs	t	*P* (perm)	Unique perms
1953-61, 1962-71	0.62589	0.7044	1226
1953-61, 1972-05	2.3539	**0.002**	9300
1962-71, 1972-05	2.4751	**0.0008**	9629