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Extinction in Eden: identifying the role of climate change in the decline of the koala in south-eastern NSW

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Abstract

Context. Reviews of climate change in Australia have identified that it is imposing additional stresses on biodiversity, which is already under threat from multiple human impacts.

Aims. The present study aimed to determine the contributions of several factors to the demise of the koala in the Eden region in south-eastern New South Wales and, in particular, to establish to what extent climate change may have exacerbated the decline.

Methods. The study built on several community-based koala surveys in the Eden region since 1986, verified through interviews with survey respondents. Historical records as far back as the late 19th century, wildlife databases and field-based surveys were used to independently validate the community survey data and form a reliable picture of changes in the Eden koala population. Analysis of the community survey data used a logistic model to assess the contribution of known threats to koalas, including habitat loss measured as changes in foliage projective cover, fire, increases in the human population and climate change in the form of changes in temperature and rainfall, to the regional decline of this species.

Key results. We found a marked, long-term shrinkage in the distribution of the koala across the Eden region. Our modelling demonstrated that a succession of multiple threats to koalas from land use (human population growth and habitat loss) and environmental change (temperature increase and drought) were significant contributors to this decline.

Conclusions. Climate change, particularly drought and rising temperatures, has been a hitherto hidden factor that has been a major driver of the decline of the koala in the Eden region.

Implications. Development of strategies to help fauna adapt to the changing climate is of paramount importance, particularly at a local scale.

Additional keywords: community survey, drought, fire, hunting, land-use change, logging, *Phascolarctos cinereus*, temperature.

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Introduction

Reviews of climate change in Australia have identified that it is imposing additional stresses on biodiversity, which is already under threat from multiple human impacts (Hughes 2003, 2012; Pittock 2009; Steffen *et al*. 2009; Driscoll *et al.* 2011; Garnaut 2011; Lunney and Hutchings 2012). Analyses of climate trends over the past five decades (1960–2009) have shown that Australian mean temperatures have increased by ~0.7°C and will continue to rise by 0.6–1.5°C by 2030 (CSIRO and Bureau of Meteorology 2010). Climate change is predicted to have an impact on wildlife on many fronts, and Kingsford and Watson (2011) made the distinction between acute impacts that are discrete, such as storms, droughts, fires and extreme rainfall events, and continuous, chronic impacts occurring over decades, such as gradual increases in mean temperatures and decreases in seasonal rainfall. Distinguishing the impacts of climate change from previously acknowledged land-use threats to wildlife is a challenge, but it is essential to achieve effective conservation planning (Felton *et al*. 2009).

The koala (*Phascolarctos cinereus*) has been affected by land-use change (Phillips 1990; Melzer *et al*. 2000; McAlpine *et al*.

2006; Rhodes *et al*. 2011) and by climate change (Seabrook *et al*. 2011; Lunney *et al*. 2012*a*). In the present study, we examined both simultaneously. The koala was once widespread through eastern Australia; however, broad-scale land clearing and logging, exacerbated by hunting for pelts, predation and disease, resulted in a dramatic decline following European settlement (Reed and Lunney 1990; Reed *et al*. 1990; Gordon and Hrdina 2005; Menkhorst 2008). The koala is listed as a threatened species in New South Wales (NSW) under Commonwealth as well as under State legislation. Several factors that reflect human population increase also threaten koala recovery, such as dog predation and vehicular collisions. The impact of climate change on koala populations is increasingly being recognised, particularly through increased drought and heatwaves (Seabrook *et al*. 2011; Lunney *et al*. 2012*a*), decreased leaf moisture (Ellis *et al*. 2010) and decreased leaf nutrition (Lawler *et al*. 1997; Gleadow *et al*. 1998; Barton *et al*. 2010; Moore *et al*. 2010).

To distinguish the impact of climate change from the suite of existing threats that have an impact on wildlife at a local scale, long-term datasets on local populations and their changing environments are required. Any species with a record that spans many decades, preferably a century, becomes a potential case study for interpreting the causes of wildlife population changes. We have long-term datasets for the koala population in the Eden region of south-eastern NSW, as well as local records of land-use change, human population increase and climate change.

Lunney and Leary (1988) established that the Eden region supported a koala population of sufficient size to sustain a pelt trade at the end of the 19th century. Since European settlement in 1830, Eden has undergone a succession of land-use changes from broad-scale land clearing for agriculture to intensive logging and rural and urban development (Reed and Lunney 1990; Reed *et al*. 1990; Lunney and Matthews 2002; Penna 2004; Recher *et al*. 2009). Reed and Lunney (1990) identified that koalas had declined in parallel with these land-use changes. By 1970, the once abundant koala populations had declined to a handful of largely isolated populations in the hillside forests on the edge of the fertile Bega and Towamba valleys and around Bermagui. These forests have been at the centre of an ongoing debate between wildlife conservation and forest harvesting that began with the launch of the Eden woodchip industry in 1968. Lunney *et al*. (1997) detailed the distribution of the remaining koalas in the region through a targeted community survey in 1991, and predicted their regional extinction.

In the present study, we aimed to determine the contributions of multiple threats to the demise of the koala in the Eden region and, in particular, to establish to what extent climate change may have exacerbated the decline. First, we determined the current regional distribution of the koala through community survey. Second, we compared the current distribution with previous community surveys and the historical record to determine the changes in koala distribution over the past five decades. Finally, we modelled the change in the regional koala population against changes in the human population, fire, foliage projective cover and climatic variables, particularly temperature and rainfall, so as to distinguish among the multiple causes of koala decline from 1975 to the present.

Materials and methods

The Eden region

The study area of ~7000 km^2 in south-eastern NSW was the Bega Valley Shire Local Government Area and it included all land tenures (Fig. 1). It corresponds closely with what is designated as the Eden Woodchip Agreement Area. It did not include the forests to the north-west of the Eden Woodchip Area, near Numeralla, which are occupied by the Southern Tablelands koala population. The National Parks and Wildlife Service (NPWS) estate is 299 904 ha and State Forests make up 217 095 ha of the Eden Woodchip Agreement Area. The changing tenure of State Forest and National Park is covered in Lunney and Matthews (2002). The region features a rise in altitude from the coastal strip to the tablelands, which is 701 m above sea level at Bombala on the western margin of the region. The area is drought prone (NSW Department of Industry and Investment 2011).

Koala presence data from community survey

We obtained historical and recent records of koalas through a series of community wildlife surveys (Reed *et al*. 1990; Reed and Lunney 1990; Lunney *et al*. 1997, 2009) to determine koala presence and locations in the Eden region from 1965 to 2010. Community wildlife survey is defined here as a survey of community members for the locations of current or historical koala sightings. Following the principles of Dilman (2007), we combined the results of a succession of four, map-based community surveys of koala sightings conducted by the authors in 1986–87, 1991, 2006 and 2009–11 to obtain a measure of change in koala distribution in the Eden region. The methods of the first three surveys of 1986–87, 1991 and 2006 are described in Reed *et al*. (1990), Lunney *et al*. (1997) and Lunney *et al*. (2009), respectively. The first survey in 1986–87 and the 2006 survey were broad-scale NSW-wide postal questionnaires, and the 1986–87 survey also involved a review of historical material and anecdotal reports (Reed *et al*. 1990). The 1991 and 2009–2011 surveys focussed solely on the Eden region, and the data collected from these surveys were verified and augmented by follow-up interviews with respondents, interviews with local experts, and through media and historical reviews.

The latest survey, in 2009–11, was a web-based survey with verification conducted specifically for the purposes of the present study. This web survey formed part of an ongoing NSW-wide fauna-monitoring project undertaken by the Office of Environment and Heritage NSW (OEH) (D. Lunney and I. Shannon, pers. comm.). The web survey was first launched in mid-2009 and requested participants to report observations of 10 easily recognisable species including the koala. An interactive map was provided and respondents were asked to mark the location of their house and the location of the species they had seen, using individual icons to distinguish the species. We re-launched the web survey in February 2011 as an Eden-specific survey under a unique web address (http://www.conservationresearch.com.au/eden.html). Media releases about the web survey were circulated to the local newspaper (*Bega District News*) and numerous local community volunteer and environment networks including the Far South Coast Catchment Management Network, Landcare, the Crossing Education Trust,

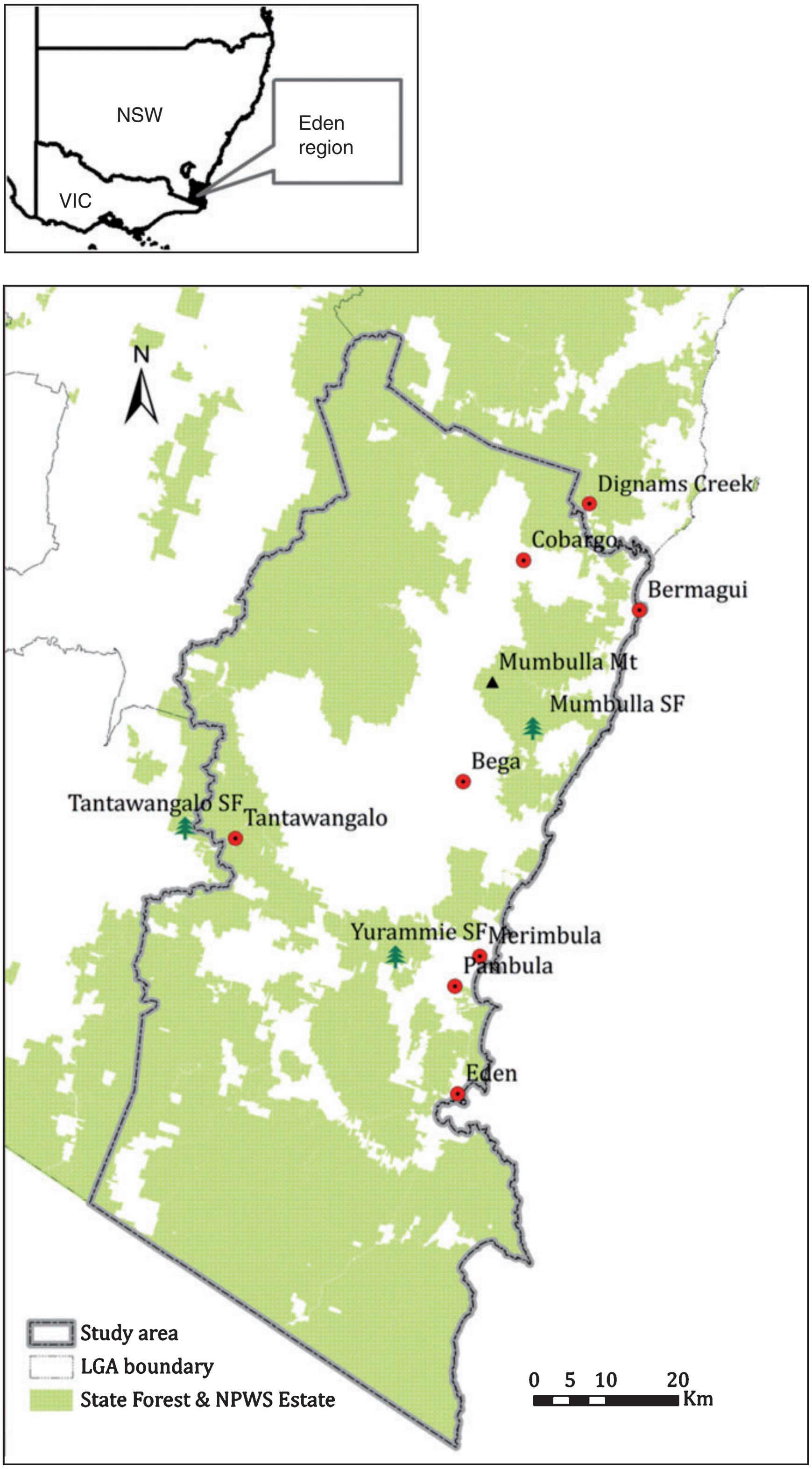

Fig. 1. The Eden study area. The shaded area represents State Forest and National Parks and Wildlife Service Estate. The outline of the study area is the Bega Valley Shire local government area.

Sapphire Coast Marine Discovery Centre and Bournda Environmental and Education Centre. An interview about the survey was broadcast over ABC Radio South East.

One of us (ES) worked locally as a field officer for 6 weeks in February and March 2011, immediately after the launch, to further publicise the survey, augment the data through face-to-face interviews, verify sightings and follow up additional sightings and information leads. Eden koala sightings obtained from the 2006 mail-out questionnaire and the 2009–11 web-based survey were verified following the method of the 1986–87 and 1991 community surveys (Reed and Lunney 1990; Lunney *et al*. 1997). Respondents were contacted by telephone to arrange a face-to-face meeting or were interviewed over the phone. Respondents were asked to provide further information to validate each koala sighting, including the year and month of the sighting, the precise location, whether the koala was dead, alive, or appeared to be unwell, whether they personally saw the koala or whether it was indirect evidence or second-hand information, and whether they had any additional sightings they had not yet reported or knew of someone who had. Second-hand koala sightings were verified with the original observer where possible. Only the koala records that could be verified were used in the logistical modelling of species distribution change.

Independent validation of koala presence data from community surveys

Koala records were obtained from a variety of other sources, outlined below, to independently validate the locations and dates of the community survey koala records and form a reliable picture of the changes in the Eden koala population. Koala records obtained from all sources were converted into latitude and longitude grid-reference points (based on the Geocentric Datum of Australia 1994, GDA94) using geographic information systems (GIS) in ArcGIS version 9.3 (ESRI Redlands, California, 2008) for visual comparison, validation and modelling, but only the verified koala records obtained from the four community surveys were retained for statistical modelling.

Field-based surveys for koalas, principally the on-ground search for koala dung (i.e. pellets), have been conducted by Chris Allen (OEH), community organisations and by a large number of volunteers since the early 1990s. Similarly, Forests NSW has undertaken repeated surveys for koalas on State Forests. The results of these local investigations are compiled in over 50 reports including published reports (e.g. Forestry Commission of New South Wales 1988, 1989; Jenkins and Recher 1990; Pyke and O'Conner 1991; Jurskis *et al*. 1994; Cork 1995; Cork *et al*. 1995; Jurskis and Potter 1997; Forests NSW 2005; Eco Logical 2006) and unpublished reports prepared by both local community and government groups (principally, Allen 1992, 2003, 2004, 2010*a*, 2010*b*; DECCW 2010). We obtained these reports online or directly from Forests NSW and OEH, and recorded the location, approximate survey effort and results of all reported local koala searches, and then confirmed our review through consultation with OEH and Forests NSW staff. Historically, site-specific surveys have been conducted in areas where koala sightings had been previously reported. These were principally in State Forests. The most recent and comprehensive site-specific koala surveys have been undertaken as part of a regional koala-monitoring project employing the grid-based spot assessment technique (SAT survey, DECCW 2010; Phillips and Callaghan 2011).

These local investigations were a primary source to validate community records and to confirm that koala populations that had been present were no longer extant.

Other important sources of koala records used to independently verify the community survey records included the Atlas of NSW Wildlife database (Wildlife Atlas), wildlife carer records and published manuscripts. The Wildlife Atlas (OEH 2011*a*) is an online database of flora and fauna records logged in from a range of sources including OEH and Forests NSW surveys, private consultancies and incidental sightings from the general public. Records of koalas that had gone into care were also obtained from the Wildlife Information and Rescue Service (WIRES) and Native Animal Network Australia (NANA) rehabilitation-group databases and via direct interviews with local convenors. Published scientific studies that were reviewed for koala records include Braithwaite (1983), Braithwaite *et al*. (1988), Lunney and Leary (1988), Lunney and Moon (1988), Cork *et al*. (1990), Reed and Lunney (1990), Jurskis (2001), Jurskis *et al*. (2001) and Lunney *et al*. (1997).

Climate and land-use change

We obtained several GIS data layers of environmental and land-use changes over time from various sources, to model these against a change in koala distribution. These layers were foliage projective cover (FPC), the density of human dwellings, fire occurrences in State Forests and National Parks, the mean annual number of days with temperatures above 35°C, and mean annual rainfall from 1975 to 2011. All GIS layers were adjusted to a spatial resolution of 1 km^2.

Time-series vegetation-cover data were generated from the NSW FPC data for woody areas for the years 1988–2008 (OEH 2011*b*). These data represent the amount of overstorey and mid-storey woody vegetation in NSW. The value ranges between 0 and 100, where 0 represents no tree cover and 100 represents dense forest. In the present study, we employed the term 'vegetation change' to cover all causes of change in foliage cover, including habitat loss caused by human activities. Thus, the model term 'vegetation change' does not distinguish between logging and land clearing. It also includes the losses in leaf cover during droughts and increases in leaf cover in wet years.

We obtained detailed logging data from Forests NSW, the NSW government body that manages logging in State Forest. These data were restricted to those forests in the current State Forest tenure that were established in 1999, following the Eden Regional Forest Agreement (RFA). This excludes all areas that were logged before the RFA, such as Tantawangalo. We, therefore, could not use these limited logging-data layers in the modelling, and relied on the FPC data.

Data on the number of households in the study area were obtained from census data for each of the 5-yearly censuses from 1986 to 2006 (Australian Bureau of Statistics 2011). Household density represents the density of human population in the region and has an indirect impact on koala populations because it is associated with the density of domestic dogs and road traffic, which directly threatens koala populations (Melzer *et al*. 2000; Lunney *et al*. 2007; Commonwealth of Australia 2009).

Fire occurrences in State Forests and National Park estate were obtained from Forests NSW (2011) and the OEH Spatial Services. These layers include areas of prescribed burns and wildfire from 1984 to the present.

Daily maximum-temperature and mean annual-rainfall data were obtained from the Australian Bureau of Meteorology (2011). Temperature data were obtained from 195 weather stations and rainfall data were obtained from 360 stations across the Australian continent. Maximum daily-temperature and mean annual-rainfall maps were generated using ANUSPLIN software (http://fennerschool.anu.edu.au/research/products/anusplin-vrsn-44#acton-tabs-link–tabs-fenner_product_tabs-middle-1, verified 24 March 2014) (Fig. 2), which uses thin-plate smoothing spline-based climate interpolation algorithms based on Hutchinson (1995). On the basis of the daily maximum-temperature maps, we estimated the mean annual number of days of daily maximum temperature above 35°C in the Eden region between 1975 and 2010.

Change in koala distribution and logistic modelling

The GIS analyses and mapping were undertaken using ArcGIS version 9.3 (ESRI 2008). The locations of koala sightings from the four community surveys were used to model the changes of koala distribution against climatic variables, FPC, fire and dwellings. If a koala was observed in a 1-km^2 grid area, then a

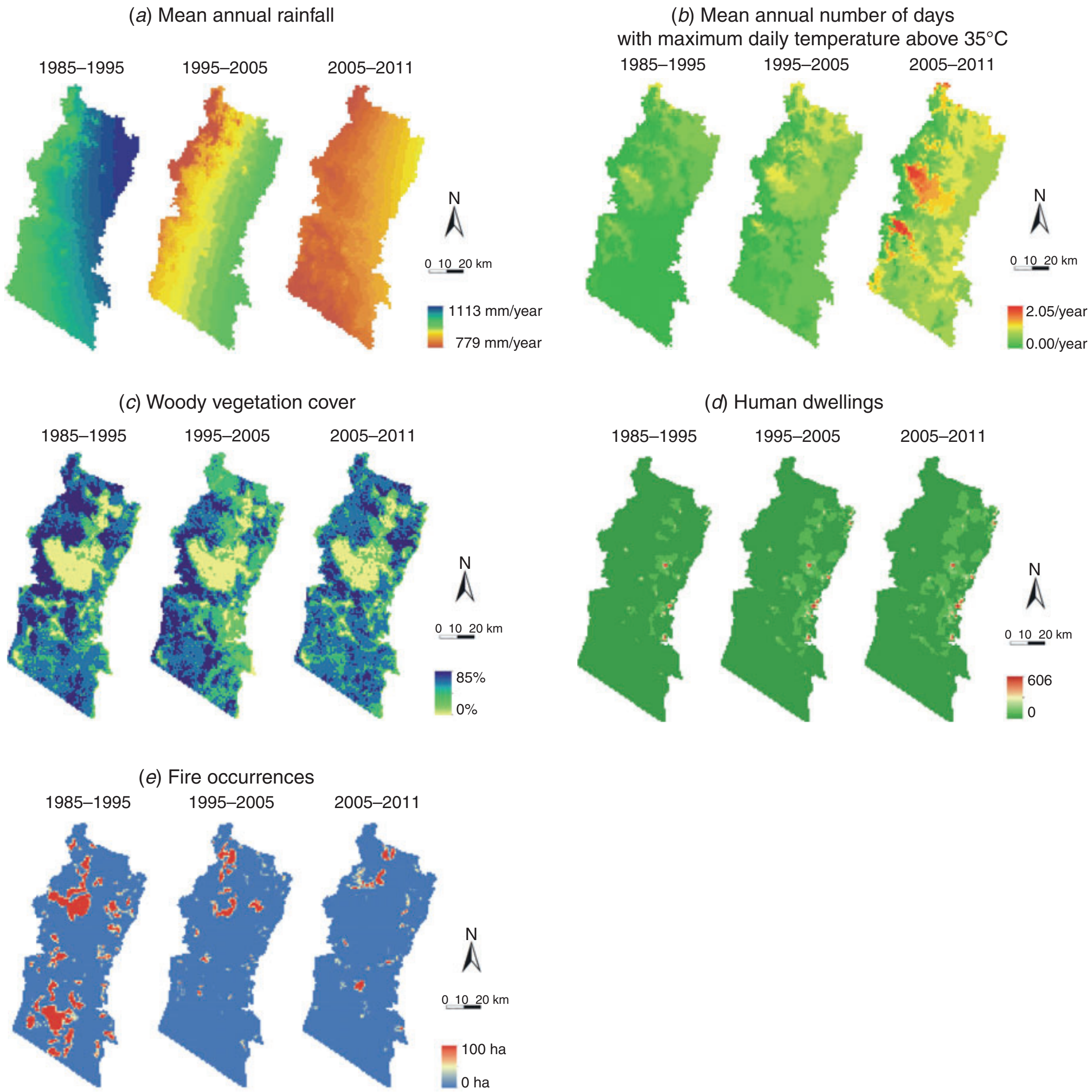

Fig. 2. Maps of the variables used in the modelling for the Eden region, with spatial resolution of 1 km. The climatic variables were created by using the ANUSPLIN software (Hutchinson 1995).

value of presence was assigned to that grid. Because absence records of the koala were not available, we generated pseudo-absence data points, as many as the number of presences, randomly across the Eden region (Elith *et al*. 2006). Randomly selected, pseudo-absences have been shown to yield the most reliable logistic-regression species-distribution models (Wisz and Guisan 2009; Stokland *et al*. 2011; Barbet-Massin *et al*. 2012).

To obtain a detailed explanation of the change of koala distributions in Eden over time, we analysed the koala-sighting records in the following four time phases: (1) 1975–85, (2) 1985–95, (3) 1995–2005 and (4) 2005–11. We modelled the distribution of the koala in the initial phase (1975–85) as a logistic function of the amount of vegetation cover (FPC value) and human dwellings, fire occurrences, the mean annual number of days with maximum daily temperature above 35°C, and mean annual rainfall that occurred in that period, i.e.

$$\begin{aligned}\text{logit}(p_{7585}) &= \alpha_{7585} + \beta_{1,7585}\text{VEG}_{7585} + \beta_{2,7585}\text{DWL}_{7585}\\ &+ \beta_{3.7585}\text{FIRE}_{7585} + \beta_{4,7585}\text{TEMP}_{7585} + \beta_{5,7585}\text{RAIN}_{7585}\\ &+ \beta_{6,7585}(\text{TEMP}_{7585} \times \text{RAIN}_{7585}),\end{aligned}$$

where p_{7585} denotes the probability of occurrence of koala between 1975 and 1985, VEG_{7585} denotes the mean FPC value for period 1975–85, and TEMP_{7585}, RAIN_{7585}, FIRE_{7585}, DWL_{7585} denote the mean annual number of days with temperature above 35°C, mean annual rainfall, number of human dwellings, and hectares affected by fire within the 1-km^2 grid between 1975 and 1985, respectively. $\text{TEMP}_{7585} \times \text{RAIN}_{7585}$ denotes the interaction effect among the climatic variables. α_{7585} and $\beta_{i,7585}$ where $i \in \{1,\ldots,6\}$ are the set of parameters to be estimated.

The koala distribution at the subsequent time phases (post-1985) was then modelled taking into account their estimated probability of occurrence at the previous time phase, the value of the fire and climatic variables within that time phase, and the change in vegetation cover and dwelling numbers from the last phase, i.e.

$$\begin{aligned}\text{logit}(p_t) &= \text{logit}(p_{t-1}) + \alpha_t + \beta_{1,t}\Delta\text{VEG}_t + \beta_{2,t}\Delta\text{DWL}_t\\ &+ \beta_{3,t}\text{FIRE}_t + \beta_{4,t}\text{TEMP}_t + \beta_{5,t}\text{RAIN}\\ &+ \beta_{6,t}(\text{TEMP}_t \times \text{RAIN}_t),\end{aligned}$$

where p_t is the probability of koala occurrence at Time phase t. ΔVEG_t and ΔDWL_t denote the change in the mean FPC value and the change in the number of human dwellings between Phases t–1 and t, respectively. TEMP_t, RAIN_t and FIRE_t denote the mean annual number of days with maximum daily temperature above 35°C, the mean annual rainfall, and the area (ha) affected by wildfire in Phase t, respectively. $\text{TEMP}_t \times \text{RAIN}_t$ denotes the interaction effect between the climatic variables at Phase t. α_t and $\beta_{i,t}$ where $i \in \{1,\ldots,6\}$ are the set of parameters to be estimated.

Parameter coefficients for all models were obtained by simulating 500 different sets of pseudo-absence data. For each simulation, we selected the best set of predictors based on stepwise Akaike information criterion (AIC) approach (Akaike 1974). We estimated the contribution of each predictor on the basis of the number of times each predictor was included in the model over 500 different pseudo-absence samples (Burnham and Anderson 2002).

To ensure robust parameter estimation, we checked whether multi-collinearity existed among predictor variables in the models for each time phase. Multi-collinearity is a problem in regression method when the explanatory predictors are highly correlated. Two highly correlated predictors can both appear non-significant, even though each would exhibit significant importance if considered individually. If two or more predictor variables are highly correlated, i.e. have a Pearson correlation coefficient larger than 0.6 (Gujarati 1995), the ways to correct this problem are to exclude one of the predictors that highly correlate with each other or to combine the correlated predictors through principal component analysis approach. The presence of spatial autocorrelation is seen as posing a serious shortcoming for hypothesis testing and prediction (Lennon 2000; Dormann 2007), because it violates the assumption of independently and identically distributed errors of most standard statistical procedures (Anselin 2002). To ensure that spatial autocorrelation is accounted for in the model, we calculated the value of Moran's I in the model residuals for each time phase. Moran's I value of a zero indicates a random spatial pattern or the absence of spatial autocorrelation, whereas a value of 1 indicates perfect spatial autocorrelation.

Results

Koala-presence data from community survey and validation

We obtained 227 verified koala-sighting records from the four community surveys, dating from as early as the 1920s to the most recent 2011 record near Bermagui, in the north-eastern corner of the region (Fig. 3). The 2009–11 web-based survey contributed three verified records. The follow-up interviews of survey respondents and community members contributed a further 20 koala records to the 2009–11 survey data. A total 46 records of koalas was obtained from the 2006 survey; however, only 30 of the 2006 records were verified directly via phone or in-person interview, whereas 16 records were reported by anonymous respondents or respondents that could not be contacted.

Respondents to both the 2006 and 2009–11 surveys came from a broad cross-section of the community, including government employees, timber-industry workers, forest conservation activists, wildlife-survey volunteers and long-term residents from farming areas. On contact, most respondents were of the opinion that koala numbers had decreased in their area over the past 30 years, however six residents contacted from the Dignam's Creek and Bermagui areas thought that koala numbers may have reached stability or increased locally following a sharp decline. There were no records of koalas entering wildlife care from the Eden region in the NSW databases of wildlife rehabilitators over the past 10 years.

Change in koala distribution on the basis of koala-presence data

Analysis of the collated community surveys revealed a marked long-term shrinkage in the distribution of the koala across the Eden region (Figs 3, 4). The contraction of the distribution shown by the community surveys was consistent with the on-ground

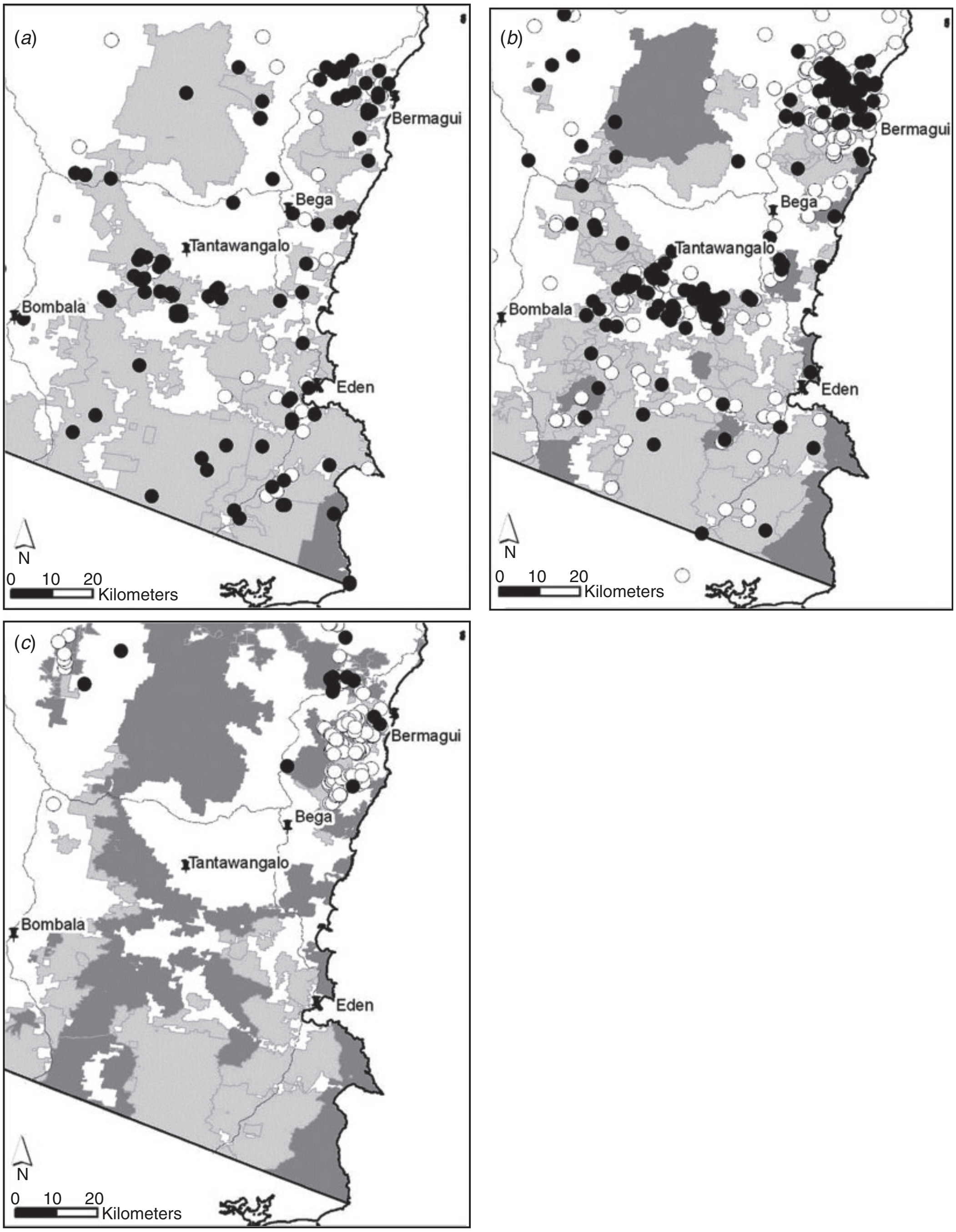

Fig. 3. A representation of the koala sightings obtained from the community-based wildlife surveys (black dots) and Office of Environment and Heritage NSW (OEH) Atlas of NSW Wildlife, other than those collected during the community field surveys (white dots). Maps show (*a*) koala sightings recorded in the Year 1979 or earlier, (*b*) koala sightings recorded between the Years 1980 and 1999 and (*c*) koala sightings recorded in the Year 2000 or later.

field-survey results, particularly those conducted by Chris Allen (OEH) and community volunteers. The distribution of the koala population in the region contracted markedly between 1980 and 1995 to two distinct and disjunct areas, namely, Mumbulla–Murrah–Bermagui in the north-east, and Tantawangalo–Yurammie approximately in the mid-region of the study area, with scattered records in the north-west and southern part of the study area. After 1996, the Tantawangalo–Yurammie population had disappeared from the record (DECCW 2010).

This shrinking koala distribution is also manifest in the supplementary koala records from the Wildlife Atlas database, wildlife carers and other local sources. When all sources of information are considered, it is clear that the koala population

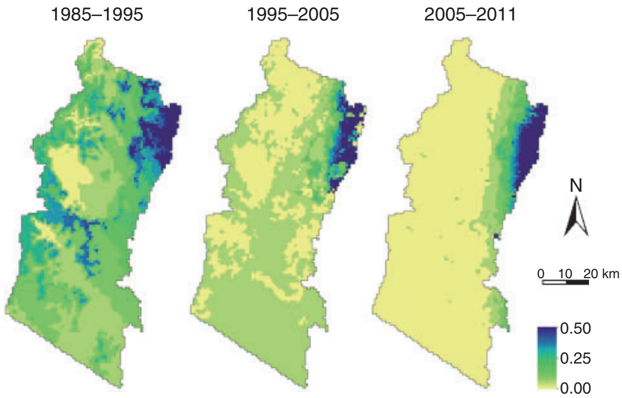

Fig. 4. The change in the probability of koala occurrence in the Eden region from 1985 to current. Dark areas represent a higher probability of occurrence, i.e. a probability of 0.5 means that there was a 50% chance of a koala sighting being reported by the community.

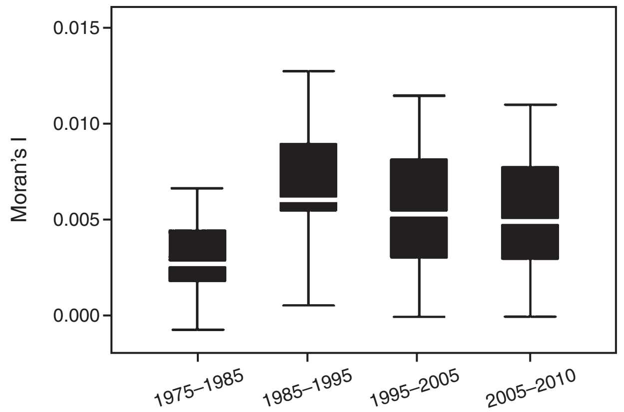

Fig. 5. The distribution of Moran's I of the model residuals for each time phase, based on 500 different sets of pseudo-absence data.

that was once located in and on the periphery of the Tantawangalo–Yurammie State Forests had become locally extinct by the end of the 1990s, as had the other koala populations, except for the north-eastern corner of the region.

Change in koala distribution and its causes on the basis of logistic models

During the modelling process, we checked whether correlations existed among predictor variables. We found that the maximum absolute Pearson correlation among predictor variables for the per-period analyses was 0.34. Therefore, we were able to include all variables in the models. Moran's I of the model residuals for each time phase were distributed around zero (Fig. 5). This indicated that spatial autocorrelation is properly accounted for in the model.

The logistic models indicated that climatic variables (increase in temperature as measured by the frequency of days over 35°C and amount of rainfall, particularly the lack thereof, i.e. drought) were the primary drivers affecting the change in koala distribution in almost every time period (Table 1). The rainfall effect was particularly strong in the last period (2005–10), where the pattern of lower rainfall was correlated with the shrinking distribution of the koala. Fire affected the probability of koala occurrence between 1975 and 1985; however, the low values in the later periods reflect the fact that fires did not overlap with the koala distribution. The increase in the human population affected the change in koala distribution, particularly in recent times (periods 1995–2005 and 2005–11), where the increase in the number of dwellings corresponded to a decline in koala distribution. In each time period, particularly from 1995 to 2005, the increase in PFC, i.e. the increase in vegetation cover (ΔVEG), led to an increase in koala distribution. This also implies that the reduction in vegetation cover caused by habitat loss as a result of human activities (e.g. logging and land clearing) and the losses in leaf cover during droughts led to a decrease in koala distribution.

The predicted distributions of koalas for the periods 1985–95, 1995–2005 and 2005–10 showed a rapid contraction of koala distribution in the Eden region since 1985 (Fig. 4). This confirmed our analysis described in the previous section. On the basis of the change in the intercept of the logistic models, it is estimated that the koala probability of occurrence has declined at an average rate of 70% every 10 years.

Discussion

The long-term trend for the koala population of the Eden region is one of drastic decline, from being sufficiently common to support a commercial pelt industry at the end of the 19th century to extreme rarity and localised extinction in most of the region by 2011. This decline points to a succession of multiple threats to koalas from land use and environmental change in the region

Table 1. The estimated standardised coefficients and the contribution of each variable in determining the change in koala distributions in the Eden region for each time-period model

Values in parentheses represent the proportion of times the associated predictor was selected using stepwise Akaike information criterion (AIC) approach, over 500 different pseudo-absence samples. A higher value indicates higher importance. See text for definition of predictor variables

Time period	Intercept	Predictor variable VEG	DWL	FIRE	TMP	RAIN	TMP × RAIN	ΔVEG	ΔDWL
1975–1985	4.12	0.52 (1.00)	–1.33 (0.02)	–0.45 (0.99)	–0.41 (1.00)	0.81 (1.00)	0.42 (1.00)	[A]	[A]
1985–1995	–3.42	[A]	[A]	[B]	–1.13 (1.00)	1.12 (1.00)	0.31 (1.00)	0.12 (0.21)	–0.35 (0.02)
1995–2005	–5.16	[A]	[A]	–0.34 (0.06)	–0.05 (1.00)	1.20 (1.00)	1.40 (1.00)	0.56 (1.00)	–6.20 (1.00)
2005–2010	–6.21	[A]	[A]	–0.38 (0.03)	–0.06 (0.85)	2.25 (1.00)	–0.53 (0.84)	0.25 (0.69)	–3.00 (1.00)

[A]Terms were not included in the modelling process.
[B]Not selected on the basis of stepwise AIC approach.

since first European settlement in 1830. Earlier studies identified hunting and habitat loss through land clearing and logging as causing this decline (Lunney and Leary 1988; Reed and Lunney 1990; Lunney *et al.* 1997); however, the potential role of climate change was not examined in these earlier studies. Our modelling demonstrated that climate change, manifest through an increased frequency of high temperatures, drought and fire, has also been a significant contributor to the regional loss of the koala over the past five decades. Anthropogenic impacts, namely vegetation loss (logging and land clearing) and dog predation, vehicular collisions and habitat degradation associated with human population increase, were taking effect in parallel to the changing climate. It was this combination of threats that contributed to the extinction of the koala population in the forests in the western and southern sectors of the region. Thus, we have identified that climate change has been a previously unrecognised driver of wildlife population decline in this region for some time.

Climate change exacerbates koala decline

Our study points to an additional impost of climate change on koalas in the context of existing threats. Our findings fit within the framework outlined by Steffen *et al.* (2009) and Driscoll *et al.* (2011), namely that climate change will exacerbate current threats to unprecedented levels. Mantyka-Pringle *et al.* (2012) found, via a meta-analysis, that the magnitude of the effect of habitat loss on biological populations depends on current and historical climatic conditions. Of particular relevance, habitat loss and fragmentation effects were greatest in areas with high maximum temperatures. Our data showed shrinkage in the distribution of Eden's koalas at a rate of 70% per decade, contracting progressively to the north-east of the region since European settlement.

Adams-Hosking *et al.* (2011) modelled the change in the core range of koalas across eastern Australia since the Quaternary and showed that their range contracted significantly to climate refugia during glacial maxima. Our climate interpolation maps for the Eden region showed that the coastal and northern forests have had a more benign range of temperatures than have the inland and southern forests of the region (Fig. 2). This helps explain the survival of the koalas in the forests north-east of Bega, particularly the forests near Bermagui, and allows the view to be formed that there were inadequate climate refuge sites in the other forests of the region.

Climate change is now recognised as an ever-increasing threat to Australia's wildlife (Lunney and Hutchings 2012). Given that the climate-change predictions are for increased temperatures and decreased rainfall in south-eastern Australia (CSIRO and Bureau of Meteorology 2010), our findings foreshadow an increasingly hostile environment for wildlife populations in fragmented habitats. The research by Adams-Hosking *et al.* (2012) added to the known list of difficulties for koalas through the predicted contraction of their required food trees with climate change. Thus, there is an increasingly urgent need to minimise those threats that can be managed locally, such as logging of koala habitat, road traffic, fire and dogs across the region, so as to maximise the chances for the existing populations to survive and to enable individuals to recolonise currently unoccupied or rehabilitated habitat.

Drought and heatwaves have been identified as having adverse impacts on koala populations in other regions (Gordon *et al.* 1988; Ellis *et al.* 2010; Seabrook *et al.* 2011; Lunney *et al.* 2012*a*). Drought was found to be a significant factor, contributing to an 80% reduction of koala numbers in western Queensland, especially on the semiarid western margin of the koala range where the remaining koalas were limited to riparian habitats (Seabrook *et al.* 2011; Smith *et al.* 2013). Ellis *et al.* (2010), working in central Queensland, found that lack of leaf moisture had an impact on koala survival during periods of high temperature. In Gunnedah, north-western NSW, a sustained heatwave during drought in 2009 caused the immediate death of an estimated one-quarter of the local koala population (Lunney *et al.* 2012*a*). Our findings showed that extreme temperatures and drought have been affecting the Eden koala population, even though it is in a coastal region and at a higher latitude than other populations known to be affected by climate change. It follows that southern or coastal populations of species do not have immunity to climate change.

Climate change is also predicted to have an impact on the nutritional quality of leaves because of rising CO_2 concentrations, and this will affect koalas across their entire range (Lawler *et al.* 1997; Barton *et al.* 2010; Hovenden and Williams 2010; Moore *et al.* 2010; Duval *et al.* 2012). The extent to which this predicted impact has affected populations of koalas has not been determined and remains a subject for future research. Nevertheless, the research points to an impact that will reduce habitat quality and therefore diminish both the capacity of the koala to adapt and the ability of managers to select suitable areas for koala survival.

Land-use change in the Eden region

Our findings implied that the reduction in vegetation cover as a result of human activities (e.g. logging and land clearing) led to a decrease in koala distribution. High-intensity logging operations, known as woodchipping, began in the Eden region in 1968. According to our results, the start of woodchipping coincided with a period of rising temperatures and drought. It thus emerges that when woodchipping began, climate change was already reducing the capacity of the local koala population to withstand this major disturbance to the forests of the region. In the present study, the frame of reference was the entire region, not logging coupes within a forest. The broader task of determining the direct relationship between logging operations and koala population dynamics, including determining any population recovery in logged coupes, would require intensive site-based research, including pre- and post-logging surveys with marked, radio-tracked koalas and other long-term monitoring techniques, such as surveys of koala dung under trees. The Eden koala population has now declined to such low numbers that a detailed impact study is precluded, but it is our view that high-intensity logging operations are a threat to koalas on the grounds that koalas are obligate tree-dwellers and logging removes their habitat. Furthermore, our models have shown that any additional impacts, such as further habitat loss, would be particularly concerning for the remaining koalas in the Eden region because their population density is very low and their vulnerability to disturbance is high. A different view was presented by Jurskis and Potter (1997) on the basis of their koala radio-tracking study in Tantawangalo State Forest. They concluded that young regrowth trees are used by koalas and that the regrowth forest after logging is likely to increase rather than decrease koala populations. That conclusion proved to be both premature and ill-judged. Our study, including the detailed field surveys by Chris Allen, has shown that the population of koalas in Tantawangalo has since disappeared. It was necessary to follow this population for a much longer time to confirm their optimistic prediction or establish what other factors were playing out.

The increasing human population, coded in our analyses as the number of dwellings, emerged as a contributing factor to koala decline, particularly from 1995 to 2005 and from 2005 to 2011. Human population encompasses domestic dogs and vehicle traffic, as well as implying an increasing intensity of forest clearing, degradation and fragmentation with the increased use of the land for housing, farming, recreation, roads and infrastructure. Our models identified that, between 1995 and 2005, the landscape matrix progressively became more hostile to koalas moving between fragments. Slight increases in the death rate of adult breeding females can have a major impact on population survival, as has been shown in other NSW coastal populations (Lunney *et al*. 2002, 2007). Given this finding, it becomes increasingly important to manage mortality factors on individual koalas, such as from dogs, cars and fire. Conversely, there are measurable advantages in tree planting, a point that arises from studies on farmland in Gunnedah, north-western NSW, and this finding can apply to any cleared area, including logged coupes, cleared land and mined land (Lunney *et al*. 2012*b*).

Management lessons for the Eden region

Among the limits to koala management in the Eden region is the lack of any detailed demographic studies. The Eden koala population is now below a threshold size for such a study; consequently, remaining options available to inform management are limited to monitoring, particularly on-ground dung searches, community survey and records from wildlife rehabilitators. Community surveys provide valuable insights on species when detailed demographic data are unavailable and they have been effective in examining trends over large scales, multiple regions and longer time periods (e.g. Crowther *et al*. 2009). The koala is iconic and recognisable, so it has been possible to track its population changes through time from local knowledge and thereby provide the opportunity for interpreting the drivers of the long-term changes.

The difficulty of establishing the whereabouts of any remnant koala populations and their likelihood of recovery creates planning dilemmas, particularly whether to focus on species recovery or broader ecosystem management (Lindenmayer 2009). Koalas were an icon in the public debate to argue for a transfer of State Forests to National Parks during the RFA process in Eden in the 1990s (Lunney 2005). As a result of the RFA decision in 1999, areas of known koala habitat, such as parts of Tantawangalo and Yurammie State Forests, were included in the new National Park estate (Lunney and Matthews 2002; Lunney 2005). It is now clear that this transfer of land was too late for conserving the koala population; however, as ghost habitat, it retains its potential to once again support a koala population should koalas recolonise this area in the future.

Conservation planning in the context of climate change

Although the south-eastern region of NSW is called Eden, with its connotation of paradise, it has been no more immune to the wildlife-extinction process than has any other region. Our examination of the long-term population change of koalas in the Eden region showed the impact of a succession of land use and environmental changes, especially in the 19th century, and emphasised the importance of managing both the species and the ecosystem holistically over long time periods. The decline of a species, such as the koala, is not peculiar in a national or global sense. It can be seen to symbolically stand for the decline of species worldwide, where sequences and combinations of threats over more than a century lead to a relentless decline to extinction.

Our findings established that climate change has been a hitherto hidden factor that has already played a significant part in the decline of the koala in the Eden region. Mitigation of the causes of climate change is a high agenda item at an international level, whereas at the local level, it is the need for adaptation strategies for individual species, where local plans of management can bring about effective change, that is of paramount importance. Landscape fragmentation means that species have limited capacity to move among regions to find climate refuges. Consequently, planning and management strategies to adapt to climate change will need to rely on effective local strategies to manage regional wildlife populations *in situ*. This will mean revisiting logging plans, instigating active restoration and environmental planting programs, endeavouring to manage the risks to wildlife from dogs and vehicles, and monitoring the success of planning strategies over a time-scale long enough for species recovery. Increasingly sophisticated datasets and modelling techniques are becoming available that allow researchers to rank the various impacts on wildlife, test predictions and monitor the success of management strategies. In turn, such detailed studies on local populations will contribute to global initiatives to conserve threatened fauna populations where climate change is exacerbating an already difficult suite of threatening processes.

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