Koalas and climate change: a case study on the Liverpool Plains, north-west New South Wales

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ABSTRACT

Koalas are prime candidates to study the impact of climate change because they are specialised folivores and lack any ready means of avoiding weather extremes. Koalas are widely but patchily distributed throughout eastern mainland Australia. Efforts to protect them from landscape-scale threats have been identified in the *NSW 2008 Koala Recovery Plan*, the 2010 NSW *Priorities for biodiversity adaptation to climate change* and the *2009-14 National Koala Conservation and Management Strategy*. The statements in the formal strategies and recovery plans identify a number of problems, two of which we address in this paper. The first problem is that of extreme weather and the second is the change of leaf quality from rising levels of carbon dioxide. This paper capitalises on our field study in Gunnedah, in north-west NSW, which examined a 1990s success story where the local koala population benefited from the plantings of trees and shrubs to hold down the water table in the face of a rising salinity crisis. In late 2009, heatwaves killed an estimated 25% of the Gunnedah koala population. This foreshadows how increased climate variability will impact on koala populations. In 2008, chlamydiosis – a disease causing infertility – had been established as being present in the Gunnedah population. The likely spread of this disease throughout the Gunnedah koala population presents a further challenge to wildlife managers in the context of a changing climate. The potential indirect effects of global climate change – how increasing concentrations of atmospheric CO_2 may reduce the availability of the nutrients in *Eucalyptus* foliage to koalas – is described and the implication drawn that elevated concentrations of atmospheric CO_2 may threaten some populations of free-ranging koalas. The Liverpool Plains are among Australia's prime agricultural landscapes where the conservation of biodiversity occurs largely on private land. Consequently, we need to integrate climate change adaptation with rural land management and restoration practices. The research demonstrates the contribution from the cross-disciplinary links. It adds to our ability to monitor sustainable native fauna populations and threatened species by distinguishing among the multiple causes of population change, and it can also be viewed as a pilot demonstrating the value of longitudinal wild population disease monitoring.

Key words: koala, *Chlamydia*, carbon dioxide, environmental plantings, land restoration, Namoi Catchment Management Authority, heatwave, radio-tracking, fauna monitoring.

Introduction

Koalas *Phascolarctos cinereus* are specialised, folivorous arboreal marsupials that do not go into torpor, fly, or shelter in hollows, and lack any ready means of avoiding weather extremes. This makes them valuable candidates to study impacts of climate change. This paper draws on our field study of koalas in Gunnedah in north-west New South Wales (NSW), to not only examine this proposition, but to progress to the next step of considering how we, as koala managers, can adapt our strategies to help the koala population cope with predicted climatic changes. The koala already faces a powerful set of threats, such as loss of habitat and fragmentation of what remains, disease, fire, and the impact of losses from dogs and vehicles. Climate change will compound these issues, accelerate adverse changes and demand a reappraisal of our approach to koala management. The koala is not unique in this predicament, but it is symbolic of the impact that can be expected on a wide range of species.

Pp 150 - 168 in *Wildlife and Climate Change: towards robust conservation strategies for Australian fauna*, edited by Daniel Lunney and Pat Hutchings, 2012. Royal Zoological Society of NSW, Mosman, NSW, Australia.

The structure of this paper examines climate change by teasing apart the separate threats of heatwave, disease, declining leaf nutrition and drought to a koala population across a prime agricultural landscape. We need to consider these impacts in the context in which we manage koalas at a local, state and federal level. Thus we begin with the conservation and management context which alerted us to the issues and empowered particular actions to be taken. We provide a field account of heatwaves that occurred in 2009 during our study of koala movement patterns and tree selection on the Liverpool Plains. We then provide a review of the likely physiological effects of elevated CO_2 on foliage composition, as well as the effects that heat and drought will have on the feeding behaviour, and thus the potential impacts on free-living koala populations. The interaction between the field data, theoretical projections in relation to climate change, and the management context allows a constructive approach to be taken for adaptive management of this iconic species.

Managing koalas for climate change - government policies

The formal policies put in place by local, state and federal governments to manage wildlife, and specifically koalas, in the context of a changing climate, provide both the means of studying the problems and the actions to be taken based on this research. The main instruments and policies, summarised below, to provide a unified context for the different strands of research covered in this paper, and it is through these mechanisms that solutions will be attempted.

New South Wales

i) The *Threatened Species Conservation Act 1995*, "Anthropogenic Climate Change" listed both as a key threatening process, and the koala, as a threatened species. There is also a *2008 NSW Koala Recovery Plan* (DECC 2008). In the plan, the following statement appears under the heading 9.2.8 *Severe weather conditions*:

"The degree of impact of natural disasters such as drought, heatwave or flood on koala populations is influenced by the quality and quantity of available habitat. These severe climatic events are expected to increase in both occurrence and intensity as a result of climate change impacts. For example, in south-western Queensland, a heatwave and drought in 1979–80 resulted in the death of 63% of the koala population in the area (Gordon et al. 1990). The animals which survived were those living in good quality habitat along permanent watercourses. In the sub-optimal habitat away from permanent water, the trees lost their leaves and the koalas were left with no food or shelter (Gordon et al. 1990).

Studies in other areas have demonstrated that during drought conditions, koalas move from drier areas to the vegetation along creeklines and rivers where soil moisture is higher (Reed and Lunney 1990). These examples illustrate the value of refuge areas when conditions become unfavourable. The widespread clearing that occurred with European settlement was primarily in the more fertile areas along watercourses; areas that would have provided refuge habitat. The loss of large areas of this vegetation has reduced the ability of koalas to survive extreme weather conditions.

Other than drought and fire, harsh conditions such as storms and snow falls have killed koalas (Reed and Lunney 1990). Such events are infrequent however, and their impact on koala populations is relatively small. These impacts may potentially increase as a result of climate change."

These descriptions of the problems are followed by a set of objectives and actions:

"Objective 1: Conserve koalas in their existing habitat… Specific objective 1a: Identify and conserve habitat important for koala conservation."

"*Action 1.3.* DECC [Department of Environment and Climate Change now Office of Environment and Heritage, OEH] will undertake and encourage other researchers to undertake population studies of koalas in a range of habitats in relation to a range of issues such as fire, drought, dogs, cars, habitat fragmentation and climate change. This action may include rural surveys (e.g. Gunnedah), peri-urban surveys (e.g. Campbelltown) and repeat surveys for already-surveyed areas. The aim of such work is to determine density, population size and trends in population dynamics."

ii) The DECCW [Department of Environment, Climate Change and Water now OEH] (2010a) statement *Climate Change Impacts New England/North West NSW*, projects that regional climatic changes by 2050 will be a moderate decrease in winter rainfall and a slight to moderate increase in rainfall in other seasons. Due to increased temperatures, drier conditions are projected, particularly in winter and spring. Days are projected to be hotter over all seasons, with the greatest warming in winter and spring (2 to 3°C). Nights are also projected to be warmer, with mean minimum temperatures projected to increase by 2 to 3°C in the east of the region, and slightly less in the west.

The DECCW (2010a) statement also notes that higher temperatures and drier conditions are very likely to have a major impact on biodiversity, and that climate change is likely to place additional pressures on those ecological communities that are already stressed due to fragmentation and may be less resilient to disturbances. The report states that fauna is likely to be affected by habitat loss, long hot spells and reduction in key habitat resources such as hollow-bearing trees and nectar. Increased fire frequencies are likely to lead to widespread changes across many ecosystems.

iii). The DECCW (2010b) NSW *Priorities for biodiversity adaptation to climate change* is a Statement of Intent in response to the listing of Anthropogenic Climate Change as a Key Threatening Process under the NSW *Threatened Species Conservation Act 1995.* This policy document recognises that a range of management strategies and mix of actions from the species level to the landscape level are needed, and that while it will be possible to build on many existing conservation programs, some adjustments and new approaches will also be necessary. Of the four key priority areas for which measures will be taken, two are most relevant to koalas on the Liverpool Plains, namely: Enhancing our understanding of the likely responses of biodiversity to climate change and re-adjusting management programs where necessary in light of this information, and Increasing opportunities for species to move across the landscape by working with partners and the community to protect habitat and create the necessary connections.

b) Commonwealth

At a Commonwealth level, the *National Koala Conservation and Management Strategy (2009-2014)* identifies both the threats and the actions to address them. The implementation of that strategy is now underway. Under the heading "6.7 Climate change", the following text is presented: "The impacts of climate change on koalas are already apparent, particularly in western Queensland and New South Wales. They include: changes in the structure and chemical composition of koala food trees; changes in the composition of plant communities and the range of important habitat species, including food and shelter trees; increased frequency and intensity of drought; increased frequency and intensity of wildfire; sea level changes which may affect the habitats of coastal and island populations; changes in average temperature, rainfall and humidity levels with consequent impacts on the extent of areas capable of sustaining koalas; and contractions in the distribution of koala populations."

"Climate change is likely to compound existing stresses of habitat loss and fragmentation, leading to higher risks from disease, and may also increase the risk of injury by dog attacks and vehicles as koalas move across the landscape in search of food."

In 2010, the Senate initiated an enquiry into the status, health and sustainability of Australia's koala population (Commonwealth of Australia 2011). The range of submissions and transcripts of the hearings show a widespread interest in the future of Australia's koala populations and the impact from a suite of threats including climate change. At the time of writing, there have been no reports from the committee undertaking the enquiry, although it can be expected to reflect the widespread concern for both current and future threats, including climate change.

The 2009 heatwaves in Gunnedah

The second strand of this paper draws on our current field study in Gunnedah, in north-west NSW. The team from the Office of Environment and Heritage (OEH), in conjunction with the University of Sydney, is capitalising on a successful 1990s program which planted trees and shrubs throughout Gunnedah, initially to hold down the water table in the face of a rising salinity crisis. Gunnedah is on the Liverpool Plains, in the Namoi Catchment Management Area in the Murray-Darling Basin. The project in Gunnedah included fitting free-ranging koalas with VHF/GPS collars (Sirtrack®, Hawkes Bay New Zealand). The GPS units recorded the location of the koala at 4-hour intervals, starting at 5 pm on the first day of recording, and continuing for a maximum six months. The aim of this project was to investigate koala movements to determine tree choice, with particular reference to their use of the environmental plantings. Extreme weather – heatwaves in late 2009 – introduced a major climate change element. This was examined in relation to: death of koalas during the heatwaves; reduced breeding rate; and the disease chlamydiosis becoming visibly manifest in the local koala population.

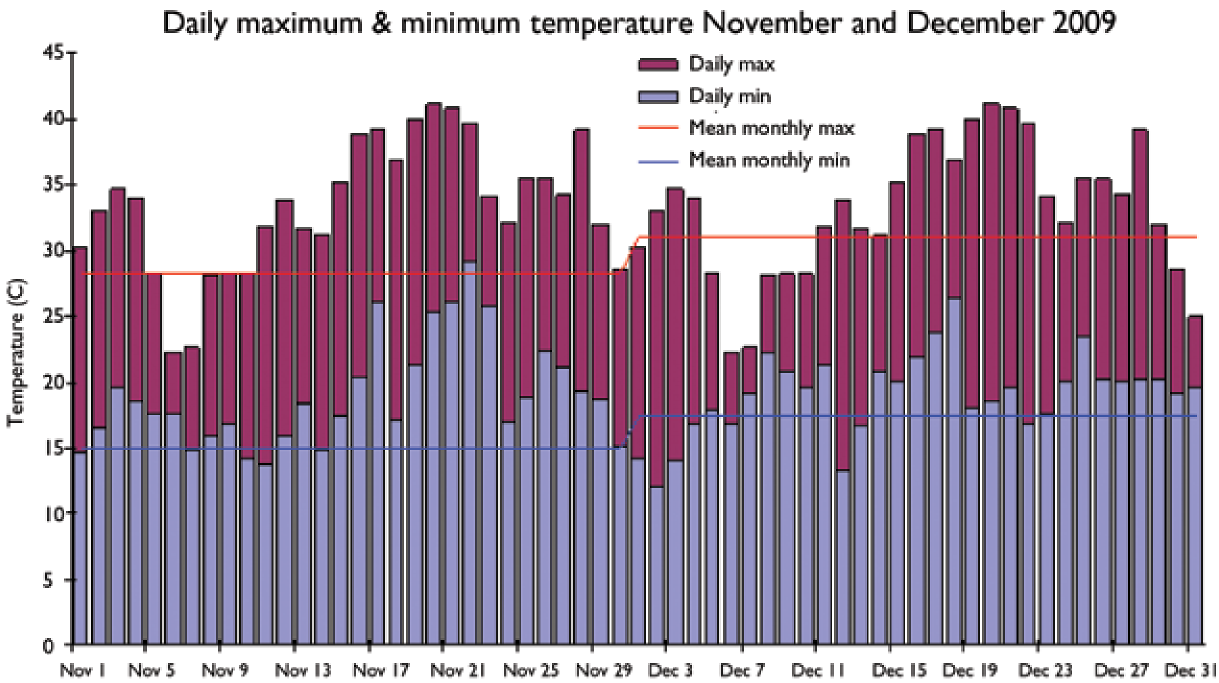

Figure 1. Daily maximum and minimum temperatures for November and December 2009 showing the succession of heatwaves in Gunnedah near the end of a long drought. The data were obtained by the Australian Bureau of Meteorology from the Gunnedah Resource Centre, where many of the koalas were captured. The monthly long-term averages of minimum and maximum are the average since 1948. The important feature of the above-average high temperatures in November and December is that they occur in a succession of days, rather than just isolated days. Further, the night temperatures are also above-average, and again occur in strings of days.

Koala deaths

There were two extended heatwaves in November and December 2009, just before the end of a long drought (Figure 1). We witnessed the visible and immediate impact on the koalas of the heatwave of December 2009. Collectively, the accounts of the behaviour and distress of the local koalas present a compelling story of the impact of a heatwave during a drought, i.e. when there is no free water.

One koala (not one of our collared study animals) was clinging low on the trunk in a Kurrajong *Brachychiton populneum* in the Gunnedah Resource Centre, 5 km from the town of Gunnedah. Kurrajongs are moderately tall (5 to 20 m high) with a dense canopy of shiny green leaves and a thick, smooth, grey-barked trunk. The pale-coloured soft, spongy wood has no commercial use (Milthorpe and Cunningham 2005), but the low branches are easily reached, making it an excellent domestic stock fodder tree during drought. The significance of Kurrajongs and other trees providing shade rises in importance in the light of our understanding of koalas endeavouring to avoid heatwaves. The koala left its tree to accept water that we offered it, initially by spraying water on its nose, then via the nozzle on the spray-gun. Our sequence of photos of this remarkable event tells part of the story of the impact of a heatwave (see Appendix). After the koala felt the water on its nose, it then sprinted to John Lemon, who was holding the spray-gun. It clasped his hand to stop John Lemon withdrawing the bottle to refill it. The koala climbed through the fence to pursue John Lemon in its quest for the water bottle. What is so remarkable is that this koala would, in any other circumstance, have quickly climbed the tree on our approach. It was manifestly desperate for water.

A local farmer (Rob Frend) reported that five of a group of about 20 koalas known on his property (Dimberoy) were found dead on the ground during the heatwave in December 2009. Another local landowner counted 12 koalas dead on his property in the same month. Two koalas that were not radio-tracked for this study were found moribund at the base of trees on two different properties (Dimberoy and Turon Park) and required veterinary intervention in the form of intravenous fluid therapy. The larger of the two koalas (ca 8 kg) required 2 litres of Lactated Ringer's solution to survive, while the smaller (ca 5 kg) required 1 litre of this solution. These volumes totalled approximately 20-25% of their body weight. Severe dehydration (> 10%) is commonly associated with death in other species (Sherman *et al.* 1983) and death would presumably have occurred in these animals without intervention. These two animals recovered and were released, but were not radio-tracked.

Of our 15 koalas radio-tracked during summer 2009, two suffered from dehydration and needed veterinary treatment (intravenous fluids for rehydration as described for the two koalas above that were not in the tracking program). Further, two radio-tracked koalas were found dead in this time period, which we attribute to dehydration, there being no other obvious explanation. If these figures are indicative of the local population, then at least a quarter of all the Gunnedah koala population would have perished in these heatwaves. As the local veterinarian, David Amos, commented at the time, "The local koalas will be dropping like flies." This view was quite clear to the local landowners whose stock were also suffering from the heatwave. The combination of drought and heatwave had proved to be lethal to the Gunnedah koala population.

In late December 2009, it rained in Gunnedah as the drought broke. A common observation by the residents of Gunnedah was that koalas were drinking in pools at the edge of the road (J. Lemon pers. obs.). This was so remarkable that photos were included in the local press, the *Namoi Valley Independent* (22/12/2009, Appendix). Reports and photos of town koalas drinking from dog bowls during the drought were also made in the *Namoi Valley Independent*. Since water was freely available to koalas living in urban areas of Gunnedah such as in dog bowls, the impact of the drought on the koala population as a whole may not been recognised by the town residents. However, the severity of the drought and the heatwave on koalas had been noticed by people living on rural properties.

Reduced koala fertility and population size

In the spring (October) of three successive years (2008-2010), we caught koalas with the primary aim of fitting them with radio-tracking/GPS collars. At each of the three spring catching and collaring field trips, we identified whether females had young on their back and inspected their pouches to check for the presence of young. We defined the fertility of the population as the proportion of females with dependent young, irrespective of the age of the offspring. The results show that the percentage of young was similar in 2008 and 2009, but it had sharply declined by October 2010 (Table 1). Most females had young, despite the drought, in October of 2008 and 2009. By October 2010, the drought had broken and the Liverpool Plains were visibly green. The low level of fertility is interpreted here as a delayed impact of the drought and the heatwaves in November and December 2009 on the health and condition of the koalas. In addition, koala admissions to the local veterinary hospital had dropped from about 4 per week, to about one per month over the last three years, i.e. about a 16-fold decline (David Amos pers. comm. April 2011). This decline may indicate a fall in size of the Gunnedah koala population.

Table 1. Number of female koalas with young caught in Gunnedah.

Date	Number of adult females	Number of females with young	Percent females with young
October 2008	8	6	75%
October 2009	9	8	89%
October 2010	10	4	40%

Disease

In 2010, the health of the koalas sampled from the population appeared to have declined, and not only was the proportion of females with young lower in 2010 than in 2008 and 2009, but chlamydiosis, an infectious disease impacting fertility, was confirmed in this population and was clinically evident. Gunnedah had previously been considered (anecdotally) to be free of this disease.

In October 2008 and 2010, there was a detailed veterinary inspection and sampling of each koala that went into the collaring program; with a particular emphasis on the status of chlamydial infection and clinical disease in the population (see photos in Appendix). The anecdotally-reported status of Gunnedah's koalas being *Chlamydia*-free had attracted our attention. The polymerase chain reaction (PCR) results for 2008 show that 2 koalas of 12 were carrying *Chlamydia pecorum* (8%), however there was little evidence of clinical disease at this time, with one animal showing a mild to moderate conjunctivitis consistent with chlamydiosis.

Preliminary real time PCR results in 2010-2011 suggest an increased prevalence of chlamydial carriage in the population (approximately 43%, unpublished data). Further, clinical disease, previously undescribed in Gunnedah koalas (David Amos pers. comm.) was now evident in both males and females. Of particular interest was the finding that older females, caught in April 2011, showed no evidence of recent breeding, a situation commonly encountered in populations where clinical urogenital chlamydiosis is a frequent occurrence (McLean 2003). In particular, one animal exhibited signs of rump pelage stain and incontinence most frequently associated with structural chlamydiosis, a condition associated with infertility (McLean 2003; Higgins *et al.* 2005) and one large male had clinical bilateral chlamydial conjunctivitis confirmed by real time PCR (see Appendix), which can cause blindness impacting survival.

Of primary importance is that, in October 2010, a large male koala was conspicuously clinically *Chlamydia* positive. He was taken into care in Waterways Wildlife Park, managed by carer Nancy Small, under the authority of David Amos and treated with chloramphenicol (60 mg/kg subcutaenous injections twice daily for 42 days) and released after confirmation of cure by real time PCR. He entered the radio-tracking program, and was recaught in April 2011, at which point there was no clinical evidence of recurrence of disease.

Climate change and koala physiology: a review

The potential physiological effects of elevated CO_2 on the nutritional ecology of koalas

Increasing concentrations of atmospheric CO_2 may reduce the availability of the nutrients in *Eucalyptus* foliage to koalas. This change in leaf quality will affect all koala populations across their range, from tropical Queensland to southern Victoria. However, the management of koalas will be at the population level. The impact of climate change on individual koala populations can be expected to vary with the local conditions. In addition, 53% of *Eucalyptus* species currently have ranges spanning less than 3°C of mean annual temperature, with 41% having a range of less than 2°C, and 25% with less than 1°C (Hughes *et al.* 1996). Twenty-three percent of species have ranges of mean annual rainfall that span less than 20% variation (Hughes *et al.* 1996). The conclusion drawn is that, "within the next few decades, many eucalypt species will have their entire present-day populations exposed to temperatures and rainfalls under which no individuals currently exist" (Hughes *et al.* 1996). Since koalas are dependent upon a few species of eucalypt within any one location, the impact on local koala populations can be expected to be marked and wide-ranging. Land managers and wildlife managers are urged to pay attention to any proposed environmental plantings for koala habitat. Since each eucalypt species has a different bioclimatic envelope, the impact of climate change will be different for each local koala population.

Although several studies indicate how elevated CO_2 concentrations influence the chemical composition of eucalypts (see below for details), the utility of this knowledge for understanding populations of koalas is hampered by our poor understanding of the links between nutrition and population dynamics of free-living herbivores. The typical approach is to form ratios of the concentrations of foliar nutrients, especially nitrogen (positive leaf attributes) and potentially refractory substances including fibre, total phenolics and tannins (negative attributes). These ratios, however, have not provided a reliable tool for predicting the size and density of animal populations (Wallis *et al.* 2011). Part of the reason for this failure is that animals respond to the concentration of digestible (= available) nutrients rather than the total amount.

"Available N" is a new *in vitro* measure described by DeGabriel *et al.* (2008) that integrates the effects of total N, the protein binding effects of tannins and the digestibility of the foliage into a single measure that can be easily interpreted. There are several reasons why measures of total concentrations of a nutrient do not reflect what is available to animals, but in eucalypts the major reason is that tannins naturally present in the leaves can bind with dietary proteins and make them unavailable for the digestive enzymes of mammals (Wallis *et al.* 2011). The ideal way to quantify this would be to make multiple measures of the response of captive koalas to leaf that varied in the concentration of tannins, but this is very time consuming so an *in vitro* procedure is used instead. *In vitro* procedures have advantages of speed, however differences in the physiology of different species of marsupials (e.g. koalas and common brushtail possums) can mean that the results of *in vitro* measures should be seen as a guide to possible effects rather than absolute (Wallis *et al.* 2011).

If we can understand how natural variations in nutrition affect population dynamics of marsupials in the field, then we may be able to predict how changes in foliar nutrients due to climate change might affect those populations. In an important study, DeGabriel *et al.* (2009) compared the influences of total nitrogen (N) and available N on reproduction by common brushtail possums *Trichosurus vulpecula* inhabiting savannah woodland near Townsville.

They found a strong relationship between the mean available N concentration of the foliage within home ranges of individual female possums and (i) the likelihood of breeding at each opportunity and (ii) the growth rate of the pouch young. In contrast, total N did not relate to either measure of reproduction. The importance of DeGabriel *et al.*'s (2009) work is that it was among the first to link plant defence, plant nutrients and the reproductive performance of individual animals. Mothers with ranges that had higher mean foliar concentrations of available N produced more young that grew faster (Figure 2). If these patterns reflect how populations of other folivorous marsupials respond to changes in the availability of foliar nutrients, then we should be better able to predict how changes in foliar nutrients associated with elevated CO_2 might affect populations of koalas.

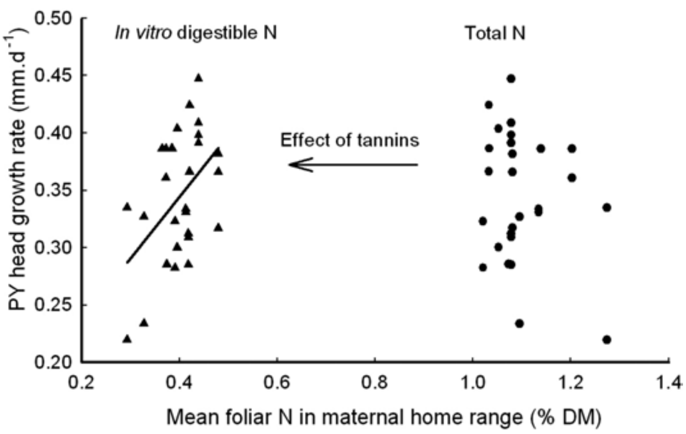

Figure 2. The association between foliar N and growth of young for brushtail possums (Source: DeGabriel ***et al.*** 2009)

Manipulative experiments indicate that increasing concentrations of atmospheric CO_2 can change many aspects of plant composition. These data, however, come predominantly from potted plants growing in glasshouses. Increasingly there are more realistic experiments with plants growing in the ground via open-topped chambers in which the CO_2 concentration around the individual plant is controlled, or via Free Air Carbon Dioxide Enrichment (FACE) experiments. Eucalypts are now being studied in both open-topped chambers and a FACE array at the Hawkesbury Forest Experiment at Richmond (Barton *et al.* 2010).

Although no study has looked specifically at the effect of elevated CO_2 on available N, studies by Lawler *et al.* (1997) of *Eucalyptus tereticornis*, Gleadow *et al.* (1998) of *E. cladocalyx* and Arlene McDowell (unpublished) of *E. ovata* measured some elements of available N in plants growing at elevated and current atmospheric CO_2 concentrations. In each study, foliar N in plants subjected to elevated CO_2 concentrations (690-750 ppm) declined by about 30% relative to controls (350-370 ppm, current concentrations are about 390 ppm). Lawler *et al.* (1997) found that the concentration of foliar condensed tannins increased by about 30% and both Gleadow *et al.* (1998) and McDowell (unpublished) found that foliar concentration of total phenolics also increased by about 30% relative to controls.

Taken together, these results suggest that, largely due to declines in total N and, to a lesser extent, a rise in the concentrations of tannins and other phenolics, available N should decline in plants growing under elevated CO_2. This suggests that aspects of leaf chemistry known to be associated with reproductive output of free-ranging folivores will change as atmospheric CO_2 concentrations rise. Thus, we could infer that elevated CO_2 will lead to significant declines in the populations of folivorous marsupials such as the koala. However, below we describe several caveats associated with this conclusion.

DeGabriel *et al.* (2009) demonstrated that even small changes in available N corresponded with large changes in reproductive success of the females and in the growth of their young. Studies of other species, including koalas, or at sites of higher fertility, may not show such steep relationships and so equivalent changes in available N may not have the same influence on reproduction. This suggests erring on the side of caution when extrapolating from a single population of common brushtail possums to a wider community of folivores. Second, we emphasize that the published data describing the effects of elevated CO_2 on eucalypts all comes from glasshouse work. Plants growing in more realistic settings possibly respond differently, with lower reductions in foliar N and these studies may also reveal the effect of drought and elevated CO2 in the water content of leaves. The results of the Hawkesbury Forest Experiment will be of great interest in this regard. Finally, in all three glasshouse studies, there were variable effects of elevated CO_2 on other secondary metabolites that could influence koala feeding. McDowell (unpublished) found no effect on foliar formylated phloroglucinol compounds (FPCs) in *E. ovata* and Gleadow *et al.* (1998) found no change in the concentration of foliar cyanogenic glycosides, although they comprised a significantly greater proportion of total N. In no study did elevated CO_2 alter foliar terpenes. The pattern of significant changes in tannins and total phenolics, but no effect on terpenes and FPCs, agrees with what we know about the relative genetic and environmental control of these classes of secondary metabolites. We cannot discount the possibility that gene-environment interactions will affect these patterns (Andrew *et al.* 2010) at different sites and in different species of folivores.

Nonetheless, what we know suggests that elevated concentrations of atmospheric CO_2 may threaten some populations of free-ranging koalas.

A physiological quandary – koalas, leaves and water

In addition to the likely changes in leaf chemistry caused by increasing concentrations of atmospheric CO_2, climate change models also predict that eastern Australia will be hotter and drier. Animals have differing reactions to heat stress, which often involves dehydration. Insights into the likely effects on koalas come from studies of Maloiy *et al.* (2008), who studied the interaction between intermittent heat stress and dehydration in several domesticated and wild ruminants from arid and semi-arid regions. Some, such as zebu cattle and Turkana goats, depressed their feeding by more than 40% when exposed to intermittent temperatures of 12 hours at 22° C followed by 12 hours at 40° C compared to a stable temperature of 22° C. Other species, such as Grant's gazelle and Oryx, did not further reduce their feeding when dehydrated and exposed to 40° C. In contrast, when dehydrated by 15% of body mass, all species ate less at an ambient temperature of 22° C. The authors concluded that selection has resulted in species that vary widely in their tolerances of heat and dehydration and that some show a remarkable resilience in maintaining digestive efficiency under these conditions. Research on different breeds of cattle suggests that animals that withstand heat stress show little increase in body temperature and little decrease in blood triiodothyronine (T3) hormone concentration (Pereira *et al.* 2008).

Animals well adapted to drought and heat can maintain their feeding partly because they can withstand the increase in metabolism due to the heat increment or specific dynamic action (SDA) of food – the energy expended in digesting and absorbing a meal and, for many animals including the koala, the cost of detoxifying secondary plant chemicals. Krockenberger (2003) estimated an SDA in koalas of 49 kJ per day, or 3% of total metabolism, much lower than that predicted (178 kJ; 10% of metabolism) for a 6 kg mammal (Secor 2009). Whatever the value, the important point is that feeding increases metabolism and requires the animal to dissipate heat. Ellis *et al.* (2010) suggested that koalas might be able to alter passage rate so that they did not digest the energy and nutrients of the leaves but just obtained water. However this is not consistent with what is known of the physiology of the koala. Although large digesta particles pass from the gut of the koala faster than do small particles, the process that effects this separation occurs after extensive digestion in the small intestine. In addition, mammals cannot produce faeces with less than about 55% of the mass being water because of physiological limits to water absorption in the colon. Thus ingested leaf that remained substantially undigested as suggested by Ellis *et al.* (2010) would lead to faecal water losses equivalent of the water gained from ingesting leaves.

We know little about the physiological reactions of koalas under field conditions of heat stress and dehydration. Clues, however, come from the population crash some 30 years ago along Mungalalla Creek in southwestern Queensland, mentioned earlier in this paper. In this forerunner to the 2009 Gunnedah incident reported here, Gordon *et al.* (1988) reported 63% of koalas dying. The conditions had a marked differential effect on animals. Those dying were dehydrated, in poor condition, had increased tick burdens, and inhabited places where the creek was dry and trees were in poor condition. In contrast, many larger, older animals remained in good condition and inhabited areas near permanent waterholes where the trees also remained healthy. This suggests a link between the water content of leaves and the health of koalas. Evidence from some of the Gunnedah koalas which actively sought water, raises the possibility that koalas drank from the waterholes, but the paucity of literature reports of koalas drinking suggests this is probably rare.

Thus, one key factor separates koalas from the various ruminants mentioned previously: koalas obtain most of their water from food and probably rarely maintain their hydration through a source of drinking water. The result is that hot and dry conditions push the koala into a physiological corner with no apparent exit. First, it is likely that leaf moisture declines during droughts, as shown by the Mungalalla Creek episode, where many trees adjacent to dried-up watercourses shed leaves. This is critical given that in more moderate conditions Ellis *et al.* (1995) observed koalas eating wet leaves and suggested they may coordinate feeding to maximise their ingestion of this source of water. Second, it is likely that the animal's water requirements increase during heat stress through evaporative heat loss, while it has minimal scope for conserving water through concentrating urine or dehydrating faeces. Thus, the animal may need to eat more to satisfy its water requirements. Eating, however, causes an increase in metabolism through SDA, placing the animal in a futile cycle: it must dissipate the additional heat by increasing its respiration rate with resultant evaporative water loss.

We can depict this scenario in the geometric framework of Simpson and Raubenheimer (1995) using two axes, to represent nutrients and water, the intersection of which represents the koala's target for nutrients and water (Figure 3). Line C represents the physiological quandary that we can expect during droughts. The leaves are drier and the koala can meet its water needs only by ingesting more nutrients. This may be possible although Krockenberger (2003) suggested that under normal conditions koalas may already be approaching the limits of gut capacity. If, however, a heatwave coincides with drought, then the heat generated by SDA may prevent a koala from eating more food and thus it will dehydrate.

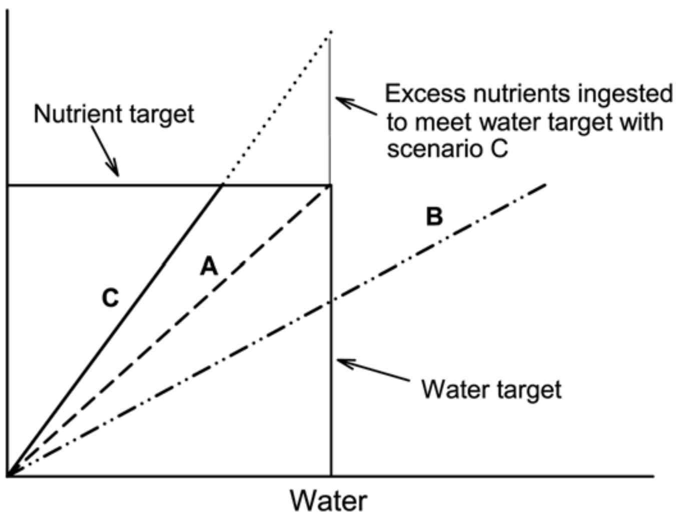

Figure 3. In this scenario, line A represents leaves containing the appropriate concentrations of both nutrients and water, so the animal will satisfy both with a minimal amount of food. In contrast, line B represents leaves with a high concentration of water so by the point that the koala meets its nutrient requirements it has well exceeded its needs for water. This is not a problem: it readily excretes the excess water as urine or moister faeces. Line C represents the physiological quandary that we can expect during droughts.

How might koalas excise themselves from this physiological quandary? In the absence of drinking water, including wet leaves, we would expect koalas to stop eating during very hot weather (or eat only at night depending on temperatures) when SDA will be less likely to cause heat stress. In summer, when nights are much shorter, this leaves a narrow window for feeding. An alternative strategy is for koalas to seek the coolest environment available, as evidence suggests they do by seeking particular trees in which to rest (Ellis *et al.* 2009), and attempt to endure a heatwave (perhaps by withdrawing water from the gut to maintain vital processes). The results from both Gunnedah and Mungalalla Creek suggest this may be true because in both cases dying koalas were severely dehydrated and in poor condition.

Discussion

An immediate and deleterious impact

From our radio-tracking data and observations of dehydrated koalas, and landowners' accounts of dead koalas where we were radio-tracking, we estimate that about a quarter of the Gunnedah koala population perished in a matter of weeks during the November and December 2009 heatwaves. Thus a combination of drought and heatwave proved to be lethal. The frequency, severity and duration of drought and heatwaves are forecast to increase under the climate change scenarios covering most of the range of the koala (e.g. DECCW 2010a, 2010b). From 2008 to 2010, the prevalence of the disease *Chlamydia* rose, foreshadowing increased rates of mortality and infertility. Simultaneously, in 2010, the birth rate fell and there were indications in early 2011, from admissions to the local veterinary surgery, that the koala population had declined sharply since 2008. The conclusion drawn from this sequence of events is that the Gunnedah koala population suffered an immediate and deleterious impact from heatwaves during the drought of 2009.

The shock of this conclusion is in its contrast to our 2006 state-wide survey of koalas in NSW (Lunney *et al.* 2009), in which Gunnedah emerged as an area with a koala population that had expanded, contrary to state trends, since the previous state-wide survey 20 years earlier. Given that the koala is a threatened species in NSW, the finding of the 2006 survey drew us to examine the Gunnedah population. We particularly focussed on the value of the environmental plantings of trees in providing additional koala habitat, especially plantings since 1990 when the "Bearcare" soil conservation initiative was launched (Smith 1992). Preliminary analyses of koala movement patterns indicate that the plantings have contributed to the expansion of the Gunnedah population; however we can now add that future tree plantings for koalas will need to consider changed climatic conditions. Thus, we need to adapt a successful environmental-planting program to cope with the projected impact of climate change. National and NSW State strategies and recovery plans have recognised this need in principle. This Gunnedah study puts that need into sharp relief.

The inevitable long-term impacts

The koala already faces a powerful set of threats from loss of habitat, disease, fire, dogs and vehicles. Climate change will compound these stresses. For example, koalas will need to search further afield for palatable leaves, trees with higher leaf moisture and shade. This will not only increase the vulnerability to dogs and vehicles as koalas walk across the ground, but the additional stress is also likely to increase the impact of diseases such as chlamydiosis on the fertility, and ultimately the viability, of the population. Further, fires will increase in both frequency and intensity with climate change (Cary 2002; Hasson *et al.* 2009; Williams *et al.* 2001), and our studies at Port Stephens, in coastal NSW, showed that fires have an immediate impact on the local koala population (Lunney *et al.* 2004, 2007). However, fires reduce habitat quality only briefly, with koalas moving back into the regenerating bush within months, and breeding within a year (Matthews *et al.* 2007). Fire is also less of an issue in Gunnedah's largely agricultural landscape.

The issue of the prevalence of the disease chlamydiosis needs special mention. While definitive evidence of prior presence of this disease amongst koalas from this region is not documented, anecdotal evidence of an experienced local veterinarian (David Amos) suggests that clinical chlamydiosis was historically (over the last 35 years) absent or extremely rare. Smith (1992), in his report of koalas and land use in the Gunnedah Shire, reported that 84% of 108 respondents to a public survey did not consider that disease was a cause of death. However, 14% said that disease was occasionally the cause of death and 2% said it was commonly the cause of death. Whether it was chlamydiosis, or some other disease, was not reported. It is an interesting, but not unexpected finding, that overt clinical chlamydiosis appears to have increased dramatically in prevalence associated with a period of intense climatic and nutritional stress. In a climatically different, but potentially similar population-stress scenario, it has been noted previously that chlamydial disease can result in infertility, contributing to population decline (Handasyde 1986; Martin and Handasyde 1999), with the conclusion that management of koala populations to minimise its impact is crucial. Although previous authors have attributed clinical signs of chlamydial disease to indicate koala populations under stress from habitat disturbance (Weigler *et al.* 1988; Ellis *et al.* 1993; Jackson *et al.* 1999) or concomitant disease (Canfield *et al.* 1991), none had considered the impacts of weather events or climate change. The ultimate expression of clinical disease is the result of a complex interaction between the host, pathogen and environment. Climate change is likely to impact directly on the environment and host dramatically, thereby changing the balance between host and pathogen significantly. In an environment of fractured habitat and peri-urban stressors, this change in balance is likely to play an increasingly important role in population viability and species survival. Although traditionally disease alone has not been regarded as a major driver of extinction (de Castro & Bolker 2005), this view is changing with two recently documented extinctions as the direct result of disease: the land snail *Partula turgida* (Cunningham and Daszak 1998) and the sharp-snouted day frog *Taudactylus acutirostris* (Schloegel *et al.* 2006).

Apart from the prevention of introduction of novel disease agents, management of the environment will become increasingly important and likely the most cost-effective and practical way to mitigate the impact of disease in wildlife populations. There may be a number of practical strategies by which this may be attempted, but revegetation programs that provide benefits in many ways may also be of assistance in this regard. The reasons as to why chlamydial disease has different clinical expression (Canfield 1989; McLean 2003) and impact on different koala populations remain unknown, however the effect appears significant in some populations and likely to increase in significance over the geographic range of the koala in the future. It is becoming more imperative to investigate chlamydial epizootiology thoroughly in different free-ranging koala populations in order to be able to develop effective management strategies to mitigate the additional effect of chlamydiosis on koala population survival. Ultimately, we need to investigate the nature of the interaction between wildlife disease and other threatening processes, with the aim of providing practical strategies to minimise the impact of disease on a wild koala population through appropriate habitat management in the face of climate change.

Drawing the lessons from Gunnedah

The Liverpool Plains are among Australia's prime agricultural landscapes; there are no national parks, and only a scattering of small state forests. The conservation of biodiversity on private land is a goal that many local landholders share, and the koala is a conspicuous example of their recent successes. While we now have a broad understanding of tree selection, patch selection and the movements of koalas between patches at a regional level, leaf physiology at the chemical level, soil status for vegetation and health status of various koala populations, what remains unclear is the inter-relationship of these factors. The challenge for adapting to climate change is to see what drives the patterns of koalas' use of habitat across an agricultural landscape.

One of the advantages of research in Gunnedah is that we are working with the Liverpool Plains Land Management, a community-based natural resource management organisation. Our project's original aim was to look at the success of the environmental plantings in the 1990s for koalas. We are examining that success, and specifically examining the extent to which environmental plantings have propelled that success. Climate change looms as a new threat, and the response will be to undertake further targeted plantings in locations where there is moisture in the ground during droughts. We also need to recognise the lag time between establishing successful plantings and their capacity to be utilised by koalas. This will involve a better understanding of koala movement patterns and how the koalas use the landscape over the long-term, including the time period before koalas include environmental planting within their home ranges. Current data from our work in Gunnedah, and from revegetated mine sites such as on North Stradbroke Island (Woodward *et al.* 2008), indicates that this is about 10 years.

Research is needed to assess which trees koalas select in extreme conditions. Most field research includes surveys for koala dung under trees (also known as scats or pellets). We recognise that the counting of koala dung in a systematic fashion can show which trees are used, but dung counts cannot show which trees were selected in heatwaves or what was the sequence of trees selected, because of the variable rate of decay of koala dung under different conditions (Rhodes *et al.* 2011). We need to know where the koalas move to and what trees they use during the drought, and more specifically during the heatwaves at the peak temperatures in the daytime and the cooler hours at night. Thus, the next steps in the research in the Gunnedah area are to determine the night versus day tree preferences, and tree preferences in the drought. Shade trees are likely to be more important than has been recognised, and feed trees are well known to be critical. Drought has also been identified as an issue for koalas in central western Queensland (Ellis *et al.* 2010) and south western Queensland in the semi-arid regions (Seabrook *et al.* in press).

What we know about the interactions between koalas and their food trees suggests that elevated concentrations of atmospheric CO_2 may threaten some populations of free-ranging koalas. We suggest two conservation approaches: (i) identifying and protecting populations of koalas on fertile sites and (ii) dedicating additional fertile sites as part of the conservation estate and rehabilitating those sites with an appropriate mix of tree species and genotypes. The importance of soil fertility for the sustained conservation of leaf-eating marsupials has long been recognised (Braithwaite *et al.* 1984; Cork and Catling 1996; Braithwaite 2004) and significant effort is being made to conserve these better quality sites. Similarly, recent research has identified some of the causes of selective feeding by koalas, particularly among trees within a single species (Moore *et al.* 2004), and this information can be directly applied to rehabilitating koala habitat.

We are looking at a more general problem than a one-off heatwave in Gunnedah. Consequently, tree selection for plantings will now need to consider how trees are used by koalas for food, water content and resting. This is likely to require different combinations of trees, and these combinations are likely to vary through the range of the koala, and even across Gunnedah. One of the primary lessons from recent studies of habitat selection and the impact of local conditions is that while the list of issues remains the same, the rankings within the list varies sharply according to location (Crowther *et al.* 2009; Rhodes *et al.* 2008; McAlpine *et al.* 2006). This lesson also applies generally to climate change and koala populations. What we derive from Gunnedah will be relevant elsewhere, but more particularly, or at least more quickly, in the western, drier parts of its range.

Koalas cannot avoid extremes of weather, except through localised tree choice. Understanding interactions between koalas and their food is vital because it provides direct input into models that can predict range contractions under various climatic scenarios (Kearney *et al.* 2010). Modelling by Adams-Hosking *et al.* (2011), under realistic projected future climate changes, with the climate becoming increasingly drier and warmer, showed a significant progressive eastward and southward contraction in the koala's bioclimatic envelope in Queensland, New South Wales and Victoria. We agree with Adams-Hosking *et al.* (2011) that a proactive approach to conservation planning is necessary to protect the koala and other species that depend on eucalypt forests.

This case study of a koala population on the prime agricultural landscape of the Liverpool Plains, demonstrates that it is possible to incorporate basic research on koalas, from field studies to laboratory studies, simultaneously with applied strategies to conserve a local population. It also demonstrates the value of participating in the interaction between policy and field science. We argue for retaining that interdisciplinary combination to conserve our native fauna. The end users will extend beyond the Liverpool Plains, via local government and state agencies, to the federal parliament.

The observations we made in December 2009 of desperately dehydrated koalas allowed us to interpret how climate change will directly impact on koala populations. In turn, that interpretation allowed us to integrate the contributions from cross-disciplinary links, e.g. predictions of heatwaves compounding the gradual, but relentless, degradation of leaf quality for koalas as CO_2 levels rise, and the rise of *Chlamydia* and its impact on fertility. It also contributes to our grasp of how to manage for sustainable native fauna populations and threatened species by distinguishing among the multiple causes of population change. This research integrates koala conservation within an adaptation strategy for climate change. In this project, we are now considering how we, as koala managers, can adapt our land and restoration management strategies.

Acknowledgements

The OEH team remains indebted to Liverpool Plains Land Management and its CEO David Walker, and the NSW Environmental Trust (Restoration) for its vital support for this project. The assistance and co-operation of many landholders in the Gunnedah shire who helped us with this project is very much appreciated. Without them, this project would not have been possible. We are also indebted to Gunnedah veterinarian David Amos for his sustained interest in this research. We are also most appreciative of many co-workers and volunteers for their assistance during the project. We also value the editing skills of Chris Moon.

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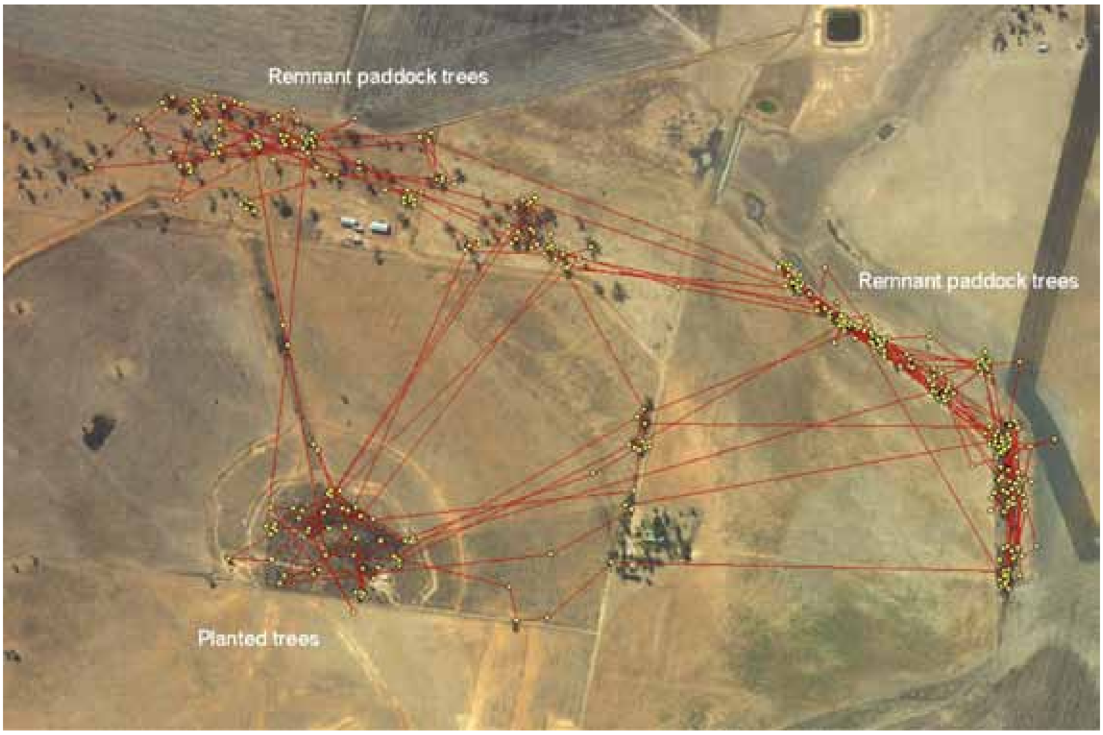
Billboard on the Kamilaroi Highway between Quirindi and Gunnedah featuring John Lemon and his daughter, Jacqui Lemon with the caption: 'Welcome to Gunnedah, Koala Capital of the World'. Photo by Dan Lunney April 2011.

This striking sequence of a koala drinking from a water bottle shows how the intense heat wave of December 2009 during the drought drove the koala to behave in an extraordinary manner. The koala depicted here is a wild koala. John Lemon (with the straw hat) misted the koala with a spray bottle normally used for watering indoor plants. The koala rushed towards John Lemon and drank from the bottle. When he attempted to withdraw the bottle to refill it, the koala embedded its claws in his hand. When John freed himself and refilled the bottle, the desperate koala wriggled through the fence and clasped John Lemon's arm. This extraordinary behaviour illustrates how dehydrated the wild koalas had become during the heat wave period. Note the dry grass showing the state of the drought at the end of 2009. Photograph D. Lunney December 2009. (Note: Rob Wheeler is the person in the cloth hat.)

While we were radio-tracking in December 2009 in Gunnedah, we noticed a koala at the base of its tree. It was so limp that it was lying on the ground. The farmer looking at it said that if it had been one of his stock, he would have shot it to put it out of its misery. We did not want to take that step. We took it to the local veterinarian (David Amos), who treated it with intravenous fluids. This large (ca 8 kg) koala required 2 litres to recover; indicating approximately 25 % dehydration, a condition very close to death. David Amos pointed out that, without the drip, it would have died of dehydration. This was one of four koalas treated in the December 2009 heatwaves. Photo by Dan Lunney December 2009.

In late December 2009, it rained in Gunnedah. A common comment was that koalas were seen drinking in pools at the edge of the road. This was so remarkable that photos were included in the local press. Photos courtesy of Marie Hobson of the Namoi Valley Independent.



The movement of koalas in Gunnedah from the data downloaded from the GPS units in the collars on the koalas shows that they use young trees, and they will cross an open paddock to reach new trees. Location: "Emerald Plains", Gunnedah.

Koala in a large River Red Gum *Eucalyptus camaldulensis*, a preferred tree species. The next steps in the research in Gunnedah include determining the night-versus-day tree preferences and tree preferences in the drought. Shade trees are likely to be more important than has been recognised, and feed trees are well known to be critical. Photo by Dan Lunney December 2009.

Koala being treated by Gunnedah veterinarian David Amos for dehydration. David Amos commented at the time that koalas would be "dropping like flies" from the heat. Photo by Dan Lunney, December 2009.

A koala hiding in a hollow in a tree on a heatwave day in Gunnedah in November-December 2009. This is an extra ordinary sight, and so rare that it is worth recording. It was found because it was wearing a radio-collar and John Lemon was tracking the koalas to check on their well-being.

Photo, John Lemon, November 2009.

The OEH team capturing a koala. Catching a koala requires a number of expert hands to assist to ensure a speedy and safe operation. The second and third photo show expert tree climber and koala catcher George Madani climbing a tree to catch a koala and the fourth shows John Lemon weighing the koala in a cloth bag. This sequence displays not only the difficulty of seeing a koala at any time of day in such dense foliage, but also that the koala was willing to walk through long grass to reach the desired tree. This sequence of photographs sits in stark contrast to those of December 2009 during a heat wave at the end of a long drought (as seen previously where the koala is drinking from a water bottle). Photographs D. Lunney October 2010 and April 2011, and E. Stalenberg October 2010.

Dan Lunney and John Lemon (in the straw hat) of OEH fitting a captured koala with a GPS tracking collar and then releasing it back into the wild with the collar. The photo on the top right shows the care taken to ensure that each collar was fitted at a comfortable tightness around the koala's neck. Photographs C. Orscheg and D. Lunney October 2010.

The Gunnedah landscape is characterized by large open fields, lines of trees and some clumps of trees as well as occasional paddock trees. In this photograph, a train is carrying a large load of coal to Newcastle. Gunnedah has a history of both mining and agriculture. Photograph D. Lunney April 2010.

Veterinarian Jo Griffith and honours student Melissa Retamales (University of Sydney) conduct a health check of a captured koala, with assistance from John Lemon (OEH) at the Gunnedah Resource Centre. All koalas captured in 2008, 2010 and 2011 were given health checks to investigate population health, breeding status and disease. Photograph D. Lunney April 2011

Clinical chlamydial conjunctivitis in a 4 year old male koala. Photograph Joanna Griffith April 2011

Rump pelage stain and evidence of urine leakage in an aged female koala. Photograph Joanna Griffith April 2011