NATURAL DISASTER RESEARCH, PREDICTION AND MITIGATION SERIES

MELTDOWN: CLIMATE CHANGE, NATURAL DISASTERS AND OTHER CATASTROPHES – FEARS AND CONCERNS FOR THE FUTURE

KATHRYN GOW
EDITOR

Nova Science Publishers, Inc.
New York

For permission to use material from this book please contact us:
Telephone 631-231-7269; Fax 631-231-8175
Web Site: http://www.novapublishers.com

LIBRARY OF CONGRESS CATALOGING-IN-PUBLICATION DATA

Meltdown : climate change, natural disasters, and other catastrophes--fears and concerns for the future / editors, Kathryn Gow.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-60876-153-1 (hardcover : alk. paper)
1. Climatic changes--Physiological effect. 2. Climatic changes--Psychological aspects. 3. Climatic changes--Social aspects. I. Gow, Kathryn.
QC903.M45 2009
577.2'2--dc22

2009025202

Published by Nova Science Publishers, Inc. † New York

In: Meltdown: Climate Change, Natural Disasters... ISBN 978-1-60876-153-1
Editor: Kathryn Gow

Chapter 11

RESPONSES OF FRESHWATER TURTLES TO DROUGHT: THE PAST, PRESENT AND IMPLICATIONS FOR FUTURE CLIMATE CHANGE IN AUSTRALIA

***John Roe*[1] *and Arthur Georges*[2]**
[1] Indiana-Purdue University, USA
[2] University of Canberra, Australia

ABSTRACT

Australia was not always arid, and the freshwater turtles that have survived to this day are either relicts residing in river systems that have themselves had a history or continuity through the drying of the continent, or they are species that have adapted in some way to meet the challenges of drought. In this chapter, we report on how Australian freshwater turtles cope with periodic loss of habitat through drought at a range of spatial and temporal scales, and consider how they might fare under changing climates predicted to occur through global warming. Global warming is not occurring in isolation of other environmental changes at a landscape scale, and we look at what interactions there might be between climate change and the increasing demands of agriculture, industry and our cities for water, in presenting challenges for our unique freshwater turtle fauna.

Keywords: turtles, drought, climate change, habitat loss, freshwater fauna

INTRODUCTION

Australia has the lowest precipitation of any vegetated continent – only Greenland and Antarctica have less – but few people realize how dry Australia actually is. To put this in perspective, the average annual discharge from all of Australia's rivers is 237,582 gigaliters

(Australian Bureau of Rural Sciences)[1] which is less than half that of the Mississippi River in North America. Consequently, much of the Australian continent is arid or semi-arid, and wetland habitats are small and poorly developed compared to other continents. As air and sea current patterns changed when Australia broke off from Antarctica, major episodes of progressive aridification occurred 30-35 Mya[2], 15 Mya and 2 Mya. The climate became not only drier, but also less predictable, and the biota that persisted had to contend with drought or periodic loss of free-standing water across much of the continent.

Drought is most simply defined as a departure below 'normal' precipitation (Dracup, Lee and Paulson, 1980; Wilhite and Glantz, 1985), although droughts can fall anywhere along a spectrum of climactic variability from long-term aridity at one extreme to annual cycles of wet and dry at the other. Aridity occurs where environmental water inputs are persistently insufficient to balance loss, whereas seasonally variable regions accrue a relatively temporary water deficit. In a sense, aridity can be considered as a long-term drought spanning millennia, whereas seasonally wet-dry climates cycle in and out of drought on a shorter term basis. The distinction between these scenarios is only a temporal one. Drought in the conventional sense falls somewhere in between, defined by water deficits spanning several years or decades compared to expectations derived over a period of historical record keeping, typically spanning decades or centuries.

From the perspective of wildlife responses to drought, this temporal distinction is important to grasp. At either end of the drought continuum, water deficits (whether short or long term) can be a relatively predictable feature of the regional climate. That is not to say that annual fluctuations in the occurrence, amount, timing, and duration of wet and dry periods do not occur – but over the balance of several years the timing and duration of water shortage occurs in a predictable sequence that has persisted for several thousands or millions of years. Such protracted periods of relatively stable climactic patterns can shape biological communities through evolutionary responses so that morphology, physiology and behaviour are suitably matched to the conditions (Ligon and Peterson, 2002; Withers, 1993). However, an abrupt departure from the normal precipitation pattern that spans several years or decades (i.e., drought in the conventional sense) may cause the existing biological communities to struggle to keep pace with the changing climate, even if environmental changes are brought about by natural climactic cycles.

The impact of drought on wildlife should not be discussed without also considering the human dimensions. Human activities may result in the imposition or exacerbation of drought conditions, and our infrastructure in developed landscapes can alter the natural responses of wildlife to drought. For instance, anthropogenic global climate change threatens to increase aridity in several regions of Australia, as well as to increase stochasticity[3] in climate, which can influence the frequency, severity, and duration of extreme weather events such as droughts (Bates et al., 2008; IPCC, 2007). Human water resource development alters water flow and hydrological regimes, in a sense simulating and hastening the onset of drought conditions and attenuating seasonal cycles of wet and dry. Roads, feral predators, and other dimensions of human society may further hamper the ability of wildlife to respond to drought.

[1] http://www.daff.gov.au/brs/social-sciences.

[2] Million years ago.

[3] Stochasticity implies irregular and unpredictable variability.

In this chapter, we introduce the Australian freshwater turtle fauna and explore how they cope (or in some cases, do not cope) with periodic loss of aquatic habitat through drought at a range of spatial and temporal scales, and consider how they might fare under changing climates predicted to occur through global warming. Global climate change is not occurring in isolation to other environmental alterations at a landscape level, and thus in assessing some of the challenges for Australia's unique freshwater turtle fauna, we examine what interactions there might be between climate change and the increasing demands of agriculture, industry and cities for water and other natural resources.

THE FRESHWATER TURTLES OF CONTEMPORARY AUSTRALIA

There are no strictly terrestrial turtles or tortoises that inhabit Australia. Instead, the Australian turtle fauna is restricted to freshwaters and the surrounding ocean. In this chapter, we focus only on those that occupy the inland freshwater systems, which are dominated by species belonging to the family Chelidae. This family of side-necked turtles is restricted to the Australasian region and South America - not even fossil forms are found outside this range (Gaffney, 1991; Williams, 1953a, b) - so it is a group with clear Gondwanan origins. Their fossil record extends back to the late Cretaceous (de Broin, 1987) in South America and the Miocene in Australia (Gaffney, Archer and White, 1989). Among extant forms in Australia and New Guinea are the river turtles in the genera *Emydura* (5 species) and *Elseya* (7 species) of northern and eastern Australia and New Guinea, and *Rheodytes* (1 species) and *Elusor* (1 species) from east coastal rivers of Queensland. The critically endangered *Psuedemydura umbrina* resides in seasonally dry wetlands of south Western Australia. Australia is also renowned for its spectacular snake-necked turtles (12 species) that range in habitat from permanent waters (*Chelodina expansa*) to highly ephemeral[4] streams and ponds (*Chelodina steindachneri*). The pig-nosed turtle (*Carettochelys insculpta*) is the only species of Australian freshwater turtle outside of the family Chelidae, belonging to the family Carettochelydidae (the only extant species in this family) that lives in the major rivers and associated wetlands of northern Australia and southern New Guinea (Georges and Rose, 1993).

Not surprisingly, given this diversity, Australia's freshwater turtles occupy a wide range of habitats - from the flooded forests and extensive swamps of the Fly River and Kikori Delta in Papua New Guinea (Georges et al., 2006a, 2008) to the dryland rivers of Australia's arid interior (Georges et al., 2006b); from the tropical north to the snow country around Cooma; from dilute waters of the sandstone plateaus of Arnhem Land and the Kimberleys (Thomson et al., 2000), to the coastal floodplains of northern Australia and the saline or brackish coastal wetlands of the Styx River in Queensland and Lake Alexandria at the mouth of the Murray River in South Australia. However, Australia was not always arid (Quilty, 1994), and the freshwater turtles that have survived to this day are either relicts residing in watersheds that have themselves had a history of continuity through the drying of the continent, or they are species that have adapted in some way to meet the challenges of drought (Georges and Thomson, 2006). Below, we explore several ways that Australian turtles respond naturally to the drying of their aquatic habitat.

[4] Ephemeral bodies of water tend to dry during drought and flood again following precipitation.

NATURAL RESPONSES TO HABITAT DRYING

Along with temperature, precipitation patterns that determine flooding and drying of surface waters are likely to be the most powerful drivers of freshwater turtle distributions and community structure[5] in Australia. Several of Australia's wetlands are under the influence of natural flood-drought cycles, and in these contexts, many turtles have adaptations to drought that allow them to successfully cope with habitat drying by moving to more permanent waters (escape in space) or by remaining in or near the dry waterbody in an inactive state to await the return of flooding (escape in time). However, several species do not regularly contend with the drying of their waterholes and may lack any evolved responses to cope successfully with drying.

Aestivation

In regions where water bodies seasonally or periodically dry, many Australian turtles have evolved specializations to survive extended periods of drought by entering a state of inactivity called aestivation (Burbidge 1981, Kennett and Christian 1994, Roe and Georges, 2007, 2008, Roe et al., 2008). The Western Swamp Turtle, *P. umbrina*, inhabits temporary swamps that flood during winter rains, but by late spring or early summer the swamps have dried and may remain so for 6-9 months (Burbidge, 1981). Several species of turtles in the genus *Chelodina* (*C. canni, C. longicollis, C. rugosa, C. steindachneri*) also inhabit wetlands that dry for several months. In some extreme circumstances, *C. longicollis* can survive aestivation for 13–16 months (Stott 1987; Roe and Georges, 2007), while others (*C. steindachneri*) may occasionally need to survive for longer time periods out of water (Cann, 1998), although in this latter case no empirical work has yet confirmed this.

Aestivation is a strategy to survive the challenges of drought by reducing the body's energy and water demands. This may involve a suite of morphological, physiological, and behavioural traits. When drought occurs, turtles may respond by leaving the wetland and seeking refuge in naturally occurring holes in the ground, or by burrowing several centimeters under soil, leaf litter, woody debris, or other structures (Burbidge 1981; Chessman, 1983; Rees 2008; Roe and Georges, 2007, 2008). Alternatively, some burrow in wetland sediment where they remain entombed until rains return (Cann, 1998; Kennett and Christian 1994). Morphological adaptations for terrestrial aestivation are perhaps best demonstrated in *P. umbrina,* which has an extensively roofed skull and an expanded shell that allows for the complete withdrawal of their head and limbs to reduce water loss. Other turtles employ physiological specializations to further conserve energy and water. For instance, *C. rugosa* reduces metabolism by 72% during dry season aestivation (Kennett and Christian, 1994), while *C. longicollis* is slow to lose water to evaporation and can further conserve water by altering the composition of excreta (Chessman, 1984; Rogers, 1966; Roe et al., 2008). While these behavioral, morphological and physiological specializations highlight adaptations that can greatly extend survival during drought, turtles are nevertheless vulnerable at this time. Predation rates can be high (Fordham et al., 2006b), and if waters do not re-flood before energy stores are depleted, turtles will eventually die of starvation or dehydration (Roe and

[5] Community structure reflects the number and types of species in an area and their relative abundances.

Georges, 2008, Roe et al., 2008). Thus aestivation is only a temporary means of increasing the probability of surviving drought, and the duration that a waterhole remains dry is a critical factor in whether turtles can persist in the area.

Movement to other Waterholes

As an alternative to aestivation, turtles may move to more permanent waterholes when drought strikes. While it is not uncommon to see turtles of several species emigrating from wetlands in Australia (i.e., when they cross roads, golf courses, lawns, or paddocks), this is one of the least well understood aspects of turtle behaviour (Roe and Georges, 2007). We have studied overland movements in *C. longicollis* at Booderee National Park and in the suburbs of Canberra (Graham et al., 1996; Kennett et al. 1990; Rees, 2008; Roe and Georges, 2007). At both sites, drought cues mass emigrations from drying wetlands into nearby permanent waterbodies. These permanent waterbodies offer temporary refuge during drought, where turtles remain (sometimes for years) before staging a return to temporary wetlands following floods. Turtles regularly travel up to three kilometers overland to reach permanent water, but occasional movements of more than five kilometers overland have also been reported in *C. longicollis* (Parmenter, 1976; Roe, 2007). However, just as the temporal duration of dry conditions is a limiting factor for survival through aestivation, an ability to escape to freshwater drought refuges depends upon the availability of waterbodies in the immediate vicinity that are somehow more resilient to drought. Most freshwater turtles could presumably traverse short distances (i.e., a few hundred meters) overland, but when farther distances must be traversed or when the intervening terrain is especially harsh, few would be capable of making such travels. Even the most basic capacities for (and limitations to) overland travel remain largely unknown for the majority of Australia's freshwater turtles.

Life History Specializations to Drying

The onset and duration of habitat drying and the return of floods can vary predictably (i.e., seasonally) or unpredictably (i.e., stochastically). It is in those species, that have to contend with unpredictability in flood-drought cycles, that we see some of the most interesting life history and behavioural "solutions" for survival. *Chelodina rugosa* deals with unpredictability in the recession of wet season flooding by laying its eggs underwater where development is suspended until the ground dries (Kennett et al., 1993a, b). Development is then adjusted so that embryos can compensate for differing durations of inundation to hatch at the optimal time prior to the onset of the ensuing rainy season (Fordham et al., 2006a). *Carettochelys insculpta* overcomes unpredictability in the onset of the wet season for its hatchlings by late-term embryonic aestivation. Eggs develop rapidly in anticipation of the wet-season floods, then enter a state of torpor within the eggshell (Webb et al., 1986). Oxygen deprivation brought about by torrential rain that floods the nest cavity brings the hatchlings out of their slumber and they hatch and make their frenzied way into the rising floodwaters (Doody et al., 2001; Georges, 1992). Hatchlings of other species, like *C. longicollis*, may emerge from eggs but remain within the nest chamber until heavy rain softens the soil and allows their escape. *Chelodina longicollis* adults have a range of adaptations that make them well-suited for both overland travel to refugial waterbodies and for extended bouts of terrestrial aestivation. This flexibility allows them to cope with drought and other unpredictable occurrences of aquatic habitat loss in a variety of ways depending on the context (Roe and Georges, 2008).

Permanent Water Specialists

Permanent water specialists[6] represent the vast majority of turtle genera in Australia, and it is these that are least likely to tolerate the drying of their aquatic habitats for any length of time. Permanent waters include lakes, ponds, rivers, and streams that typically remain inundated or maintain water flow without drying. Permanent water specialists include *Emydura*, *Elseya*, *Rheodytes*, *Elusor*, and *Carettochelys*, but *C. expansa* and *C. oblonga* also rely on habitats that do not typically dry out.

Photo: Queensland EPA Roma. Photo reproduced with permission.

Figure 11.1. When freshwater refuges with a long history of water permanence dry, permanent water specialists typically perish, such as in Lake Numalla, Queensland, where some 10,000 Murray turtles were estimated to have died.

Turtles that are rarely exposed to drying conditions typically lack adaptations that would allow them to successfully contend with habitat drying by evacuating or aestivating (Chessman, 1984; Christiansen and Bickham, 1989; Gibbons et al., 1983). However, permanent water specialists may occasionally enter areas that periodically dry, such as when river flows force them out of channels and into shallow backwaters or downstream waterholes

[6] Habitat specialists tend to occupy a narrow range of environmental conditions, whereas habitat generalists can occupy a wide range of conditions.

that can quickly become isolated when flows subside. In these scenarios, turtles can become unexpectedly stranded by drying floodwaters and many perish as a result (see Figure 11.1).

Nevertheless, some of Australia's permanent water specialists successfully inhabit arid regions, with some of the most widely fluctuating water flows on earth, and where most water can vanish for long periods. The Cooper Creek turtle, *Emydura macquarii emmottii*, has a most interesting life history, as it manages to persist in areas where other turtles cannot. This species occupies the permanent waterholes of the Cooper Creek floodplain in central Australia. Precipitation over much of the Cooper catchment is exceptionally low (approximately 330 mm per year, Australian Bureau of Meteorology,[7] but monsoonal rainfall in its headwaters results in intermittent and widespread flooding of this dryland river.

An exceptionally flat landscape results in an extensive network of distributary channels, peppered with isolated and deeper waterholes. It is in these waterholes that this species resides between episodes of floods, often in exceptionally high population densities (Georges et al., 2006b). Should waterholes dry (which happens during the worst of our droughts) the turtles perish, but when the system floods once again others are able to reinvade from refugial waterholes that did not dry. This dynamic allows this river turtle to persist in Australia's arid centre. The scale of this landscape is immense – waterholes are separated by hundreds of kilometers of arid and semi-arid land, and the temporal scale of flooding is measured in years instead of months, attributes presumably unsuited to the drought survival strategies of any other Australian turtle.

DROUGHT IMPACTS AND THE HUMAN DIMENSION

The human dimensions of drought relevant to freshwater turtles fall into two broad categories. The first is creation of conditions that either cause drought or produce drought-like conditions, and the second includes activities that limit the natural ability of turtles to respond to drought. To assess the impact of drought on turtles, we must understand how these anthropogenic dimensions interact to directly and indirectly influence their populations.

The most visible consequence of drought in freshwater systems occurs when a water body dries completely, and consequences are most severe when water bodies that typically serve as aquatic refugia also dry out. Surface waters can recede and eventually dry from decreased runoff from rainfall, inflow from rivers, or supply by groundwater. Though rainfall ultimately drives all three processes, our demands on water for irrigation, industry and municipal activities hasten the pace of drying and extends the temporal and spatial impact of drought into areas that were once more extensively flooded or served as permanent water refuges (Kingsford and Thomas, 1995; Kingsford, 2000). Reports of mass turtle mortality in drying wetlands of Australia are increasing (see Figures 11.1 and 11.2), though such reports have not yet made their way into the scientific literature, as they have in other countries (Christiansen and Bickham, 1989, Bodie and Semlitsch, 2000). Many turtles die of starvation or dehydration during or following wetland drying, but drought can indirectly cause mortality as well. Turtles emigrating from a drying waterbody are vulnerable to predators including the introduced European Fox (Spencer, 2002), or they may encounter vehicular traffic in developed areas resulting in mass mortality on roads in Australia (Chessman, 1988; Rees,

[7] http://www.adl.brs.gov.au/water2010/pdf/monthly_reports/awap_3_report.pdf.

2008), see Figure 11.3) and elsewhere (Aresco, 2005; Ashley and Robinson, 1996). Exclusion fences can also entrap turtles on land where they eventually die of exposure to predators, high temperatures, or dehydration (Anonymous 1941; JHR and AG pers. obs.).

Feral pigs can even target and depredate turtles aestivating in the mud of dry wetlands, threatening the persistence of turtle populations in northern Australia (Fordham et al., 2006b, 2007). All of the above are examples of how human alterations to natural systems interact with drought to exacerbate impacts upon turtles.

Drought can also result in important changes to habitat heterogeneity with subsequent impacts on turtles. For instance, large river systems naturally include not only the deeper and permanent channel, but during floods the aquatic habitat expands to encompass adjacent floodplain wetlands (e.g., oxbows, billabongs, marshes, and sloughs). Such flooding events resupply these highly productive and important wetlands with water and nutrients and provide a conduit for turtles to travel into them (Doody et al., 2002; Georges et al., 2006). Low rainfall and high use of upstream water during drought reduces both the extent and duration of flooding in these adjacent wetlands such that, in Australia's most developed rivers, these habitats may no longer flood at all (Kingsford, 2000; Roshier et al., 2001).

Photo: John Roe.

Figure 11.2. Receding waters can concentrate turtles, resulting in high densities. Disease and competition for food increase under such conditions, killing many individuals even before the water body dries completely such as in Lake McKenzie, Jervis Bay Territory.

Turtle communities in such systems are often spatially organized according to species habitat preferences (Chessman, 1988), and in Australia several species of turtles including *C. insculpta* (Doody et al., 2002). *C. longicollis* (Chessman, 1988), and *C. expansa* (D. Bower, University of Canberra, unpubl. data) make extensive use of these flooded backwaters. Not only would turtle community diversity decline should river floodplains fail to flood, but our work in Booderee National Park in the Jervis Bay Territory indicates that such drought-induced changes in hydrology can also occur in wetlands isolated from river flows, with subsequent effects on turtle growth, reproduction and regional abundance (Kennett and Georges, 1990, Roe and Georges, 2008).

Drought can also result in important changes to habitat heterogeneity with subsequent impacts on turtles. For instance, large river systems naturally include not only the deeper and permanent channel, but during floods the aquatic habitat expands to encompass adjacent floodplain wetlands (e.g., oxbows, billabongs, marshes, and sloughs). Such flooding events resupply these highly productive and important wetlands with water and nutrients and provide a conduit for turtles to travel into them (Doody et al., 2002; Georges et al., 2006). Low rainfall and high use of upstream water during drought reduces both the extent and duration of flooding in these adjacent wetlands such that, in Australia's most developed rivers, these habitats may no longer flood at all (Kingsford, 2000; Roshier et al., 2001).

Turtle communities in such systems are often spatially organized according to species habitat preferences (Chessman, 1988), and in Australia several species of turtles including *C. insculpta* (Doody et al., 2002). *C. longicollis* (Chessman, 1988), and *C. expansa* (D. Bower, University of Canberra, unpubl. data) make extensive use of these flooded backwaters. Not only would turtle community diversity decline should river floodplains fail to flood, but our work in Booderee National Park in the Jervis Bay Territory indicates that such drought-induced changes in hydrology can also occur in wetlands isolated from river flows, with subsequent effects on turtle growth, reproduction and regional abundance (Kennett and Georges, 1990, Roe and Georges, 2008).

The retention of water in reservoirs is a common way to meet societal water demands in times of drought, but ironically, this too can have negative effects on some turtles. For example, the Fitzroy turtle (*Rheodytes leukops*) inhabits shallow riffle zones (Tucker et al., 2001), a habitat affinity linked to its gill-like cloacal respiration and diet of aquatic invertebrate prey (Gordos, 1999; Priest, 1997). Dams that transform free flowing rivers to lake-like conditions or that otherwise alter natural flow regimes and increase sedimentation rates have degraded much riffle habitat in the Fitzroy River catchment, which has certainly contributed to the listing of *R. leukops* as a Vulnerable species (Georges, 1993). A change in turtle community diversity (typically a reduction in the number of species) often follows the construction of dams, with river (lentic) turtles being replaced by pond (lotic) turtles or species with more general habitat preferences (DonnerWright et al. 1999; Tucker et al., 2001). Our changes to natural hydrology patterns in aquatic systems are not limited to rivers, but also include modifications to still-water wetlands for increased water retention during drought (i.e., farm dams, Brock et al., 1999). In this case, humans' influence on some species may be positive, as farm dams, irrigation channels and reservoirs for water retention in agricultural and pastoral regions now offer drought refuges. The proliferation of these artificial aquatic habitats has perhaps augmented populations of *C. longicollis* in dry regions (Rees, 2008) and may even have facilitated its expansion into areas that were previously too dry (Beck, 1991). However, the persistence of these "unnatural" wetlands and the benefits they offer aquatic turtles into the future is uncertain under changing climate scenarios.

The rising salinity of freshwaters is another major issue with which turtles must contend in Australia. Rising soil salinities brought about by land clearing, intensive irrigation and reduced rates of evapotranspiration[8] have allowed water tables to rise and contaminate freshwater systems (Lemly et al., 2000), but the impact on Australian turtles in these systems has not yet been examined. We know that in some cases increasing salinities have brought saline-tolerant taxa[9] into unwelcome contact with turtles, as in the case of turtle fouling by encrusting estuarine worms in Lake Alexandria, South Australia (see Figure 11.4). Many nominally freshwater turtles may successfully utilize saline environments (Dunson et al. 1986, Georges and Rose, 1993, Moll and Moll, 2004); however, the physiological, behavioral, and population level responses of Australian turtles to rapidly increasing salinities are in immediate need of assessment.

Photo: Damien Michael. Photo reproduced with permission.

Figure 11.3. Turtles forced to emigrate from drying waterbodies frequently cross roads in developed areas, often leading to mass mortality from vehicular collisions. This *Chelodina expansa* was killed on the Riverina Highway adjacent to the Wonga Wetlands and the Murray River.

[8] Evapotranspiration is the movement of water from the ground to the atmosphere via evaporation and plant transpiration.

[9] Saline-tolerant taxa are those animals that can successfully inhabit waters with higher concentrations of dissolved salts than in normal freshwater. Freshwater typically has dissolved salt concentrations below 0.5 parts per thousand.

Photo: Sally Grundy. Photo reproduced with permission.

Figure 11.4. Increased salinization of freshwater habitats has led to the encrustation of turtles' shells by estuarine tube worms. In severe cases encrustation can impede turtle movements and limit the ability to retract their head and limbs, such as in this *Emydura* in Lake Alexandrina, South Australia.

THE FUTURE OF AUSTRALIA'S TURTLES IN A CHANGING CLIMATE

Predictions for changes to Australia's climate include a reduction in precipitation across much of the continent, particularly in the southern temperate regions. This will result in expansion of arid and semi-arid zones that are less hospitable to turtles, and an increase in the frequency, duration and intensity of drought. The recent drought in south-eastern Australia, whether or not it is part of a natural cycle, serves as a harbinger of impending climate change and focuses our attention on what might be in store for the future. Turtles in the Murrumbidgee River and elsewhere have perished in waterholes not known to dry since European colonization. The Murray-Darling River now seldom flows into the sea, and the combination reduced water flows with marine incursion and increased salinization is presenting major challenges to the freshwater turtle communities of Australia's largest river system. In the south-west, *P. umbrina*, one of the rarest turtles in the world is already on the brink of extinction, being restricted to a few small ephemeral swamps. Any further reduction in precipitation will require continual human intervention to maintain this species in the wild (Kuchling and Dejose, 1988, Kuchling et al., 1991).

If there is any reason to be optimistic, it is that this unfolding crisis has been experienced to some degree by the Australian biota before, and those species that are with us today are there because they have survived the changes. The challenge will be to determine what humans have done to reduce the capacity of the biota to survive climate change as it has done in the past. In the case of *P. umbrina*, the answer is clear. We have dramatically reduced the extent of available habitat through reclamation of swampland for urbanization and agriculture, rendering this species extremely vulnerable to climate change. In the Murray-Darling drainage and other watersheds that are currently experiencing greatly reduced flow, we need to know where the refugial areas were during past periods of drying so that we can protect their integrity during this drying event. These refugia are areas in which the turtles and other aquatic biota persisted during extended periods of low precipitation, only to expand out to their current distributions when precipitation increased. On a shorter timescale, responses to drought may involve a dynamic of localized extinction and repopulation. What have we done - in terms of fragmenting our freshwater systems through habitat degradation, construction of weirs, dams and roads, and alteration of flow intensity, duration and timing - to disrupt this dynamic? These considerations apply at many geographic scales, from the Cooper Creek watershed in the arid centre to individual wetlands and wetland networks, such as at Booderee National Park in the temperate south-east.

Conclusion

Clearly, failure to address several issues, including the maintenance of adequate water during periods of reducing precipitation, the isolation of off-channel waterbodies in the lower Murray to address human demands for water quantity and quality, the construction of more dams and storage facilities without exploring alternatives, and our increasing take from aquifers with little regulation, are all responsible for environmental changes that are likely to have major (and potentially adverse) impacts on freshwater communities, of which turtles are an integral part. Regardless of the ultimate cause of recent droughts in Australia and other parts of the world, the challenge before us is to improve water resource management in a way that allows for more efficient use of water to meet societal demands, while at the same time ensuring that the natural capacity for biota to respond to drought is maintained.

References

Anonymous. (1941). Death on the plains-where instinct fails. *Wild life* (Melbourne), 3, 13-14.

Aresco, M.J. (2005). Mitigation measures to reduce highway mortality of turtles and other herpetofauna at a north Florida lake. *Journal of Wildlife Management*, 69, 549-560.

Ashley, E.P., and J.T. Robinson. (1996). Road mortality of amphibians, reptiles, and other wildlife on the long point causeway, Lake Erie, Ontario. *Canadian Field-Naturalist*, 110, 403-412.

Bates, B.C., Z.W. Kundzewicz, S. Wu, and J.P. Palutikof (Eds.). (2008). Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva.

Beck, R.G. (1991). The Common Longnecked Tortoise *Chelodina longicollis* (Shaw 1802) (Testudinata: Chelidae): A comparative study of the morphology and field behaviour of disjunct populations. *South Australian Naturalist,* 66, 4-22.

Bodie, J.R. and Semlitsch, R.D. (2000). Size-specific mortality and natural selection in freshwater turtles. *Copeia 2000,* 732-739.

Brock, M. A., Smith, R.G.B. and Jarman, P.J. (1999). Dam it, drain it: alteration of water regime in shallow wetlands on the New England Tableland of New South Wales, Australia. *Wetlands Ecology and Management*, 7, 37-46.

Burbidge, A.A. (1981). The ecology of the western swamp tortoise *Pseudemydura umbrina* (Testudines: Chelidae). *Australian Wildlife Research,* 8, 203-223.

Cann, J. (1998). *Australian Freshwater Turtles.* Beaumont Publishing, Singapore.

Chessman, B.C. (1983). A note on aestivation in the snake-necked turtle, *Chelodina longicollis* (Shaw) (Testudines: Chelidae). *Herpetofauna,* 14, 96.

Chessman, B.C. (1984). Evaporative water loss from three south-eastern Australian species of freshwater turtle. *Australian Journal of Zoology*, 32, 649-655.

Chessman, B.C. (1988). Habitat preferences of freshwater turtles in the Murray valley, Victoria New South Wales. *Australian Wildlife Research,* 15, 485-491.

Christiansen, J.L., and Bickham, J.W. (1989). Possible historic effect of pond drying and winterkill on the behavior of *Kinosternon flavescens* and *Chrysemys picta. Journal of Herpetology,* 23, 91-94.

de Broin, F. (1987). The late Cretaceous fauna of Los Alamitos, Patagonia, Argentina. Part IV. Chelonia. Revista del Museo Argentino de Ciencias Naturales, Bernardino Rivadavia. *Paleontologia*, 3, 131–139.

DonnerWright, D.M., Bozek, M.A., Probst, J.R. and Anderson. E.M. (1999). Responses of turtle assemblages to environmental gradients in the St. Croix River in Minnesota and Wisconsin, U.S.A. *Canadian Journal of Zoology,* 77, 989-1000.

Doody, J.S., Georges, A., Young, J.E., Pauza, M.D., Pepper, A.L., Alderman, R.L and Welsh. M.A. (2001). Embryonic aestivation and emergence behaviour in the pig-nosed turtle, *Carettochelys insculpta. Canadian Journal of Zoology,* 79, 1062-1072

Doody, J. S., Young, J. E. and Georges. A. (2002). Sex differences in activity and movements in the pig-nosed turtle, *Carettochelys insculpta*, in the wet-dry tropics of Australia. *Copeia 2002,* 93-103.

Dunson, W.A. (1986). Estuarine populations of the snapping turtle (*Chelydra*) as a model for the evolution of marine adaptations in reptiles. *Copeia 1986,* 741-756.

Dracup, J. A., Lee, K. S. and Paulson, E.G. (1980). On the definition of droughts. *Water Resources Research,* 16, 297-302.

Fordham, D. A., Georges, A. and Corey. B. (2006a). Compensation for inundation-induced embryonic diapause in a freshwater turtle: achieving predictability in the face of environmental stochasticity. *Functional Ecology*, 20, 670-677.

Fordham, D. A., Georges, A. and Corey. B. and Brook, B.W. (2006b). Feral pig predation threatens the indigenous harvest and local persistence of snake-necked turtles in northern Australia. *Biological Conservation*, 133, 379-388.

Fordham, D., Georges, A. and Brook. B.W. (2007). Indigenous harvest, exotic pig predation and local persistence of a long-lived vertebrate: managing a tropical freshwater turtle for sustainability and conservation. *Journal of Applied Ecology,* 45, 52-62.

Gaffney, E.S. (1991). The fossil turtles of Australia. In P.Vickers-Rich, J.M. Monaghan, R.F., Baird, and T.H. Rich (Eds.). *Vertebrate Paleontology of Australasia* (pp. 704-720). Pioneer Design Studio and Monash University Publications Committee, Melbourne.

Gaffney, E.S., Archer, M. and White, A. (1989). Chelid turtles from the Miocene freshwater limestones of Riversleigh Station, Northwestern Queensland, Australia. *American Museum Novelties,* 2959, 1-10.

Georges, A. (1992). Thermal characteristics and sex determination in field nests of the pig-nosed turtle *Carettochelys insculpta* (Chelonia: Carettochelydidae) from northern Australia. *Australian Journal of Zoology,* 40, 511-521.

Georges, A. (1993). Settling conservation priorities for Australian freshwater turtles. In D. Lunney and D. Ayers (Eds.), *Herpetology in Australia, a Diverse Discipline* (pp. 453-476). Royal Zoological Society of New South Wales.

Georges, A., Alacs, E., Pauza, M., Kinginapi, F., Ona, A., and Eisemberg, C. (2008). Freshwater turtles of the Kikori Drainage, Papua New Guinea, with special reference to the pig-nosed turtle, *Carettochelys insculpta. Wildlife Research,* 35,700-711.

Georges, A., Guarino, F., and Bito, B. (2006a). Freshwater turtles of the TransFly region of Papua New Guinea - notes on diversity, distribution, reproduction, harvest and trade. *Wildlife Research,* 33, 373-384.

Georges, A., Guarino, F., and White, M. (2006b). Sex-ratio bias across populations of a freshwater turtle (Testudines: Chelidae) with genotypic sex determination. *Wildlife Research,* 33, 475-480.

Georges, A. and Rose, M. (1993). Conservation biology of the Pig-nosed Turtle, Carretochelys insculpta. *Chelonian Conservation and Biology,* 1, 3-12.

Georges, A. and Thomson, S. (2006). Evolution and zoogeography of Australian freshwater turtles. In *Evolution and Biogeography of Australian Vertebrates* (pp. 281-300). J.R. Merrick, M. Archer, G.M. Hickey, and M.S.Y. Lee (Eds.). Oatlands, NSW: Australian Scientific Publishing.

Gibbons, J.W., J.L. Greene, and Congdon, J.D. (1983). Drought-related responses of aquatic turtle populations. *Journal of Herpetology,* 17, 242-246.

Gordos, M.A. (1999). Physiological ecology of the Fitzroy Turtle, *Rheodytes leukops.* Honours Thesis, University of Queensland.

Graham, T.E., Georges, A., and McElhinney, N. (1996). Terrestrial orientation by the eastern long-necked turtle, *Chelodina longicollis,* from Australia. *Journal of Herpetology,* 30, 467-477.

Intergovernmental Panel on Climate Change. (2007). Synthesis Report. R.K. Pachauri, and A. Reisenger (Eds.). IPCC, Geneva, Switzerland. Available from, http://www.ipcc.ch/ipccreports/ar4-syr.htm (accessed March 2009).

Kennett, R. and Christian, K. (1994). Metabolic depression in estivating long-neck turtles. *Physiological Zoology,* 67,1087-1102.

Kennett, R.M. and A. Georges. (1990). Habitat utilization and its relationship to growth and reproduction of the eastern long-necked turtle, *Chelodina longicollis* (Testudinata: Chelidae), from Australia. *Herpetologica* 46, 22-33.

Kennett, R., Christian, K., and Pritchard, D. (1993a). Underwater nesting by the freshwater turtle *Chelodina rugosa* from tropical northern Australia. *Australian Journal of Zoology,* 41, 47-52.

Kennett, R., Georges, A., and Palmer-Allen, M. (1993b). Early developmental arrest during immersion of eggs of a tropical freshwater turtle, *Chelodina rugosa* (Testudinata: Chelidae) from northern Australia. *Australian Journal of Zoology*, 41, 37-45.

Kingsford, R. T. (2000). Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology*, 25, 109-127.

Kingsford, R.T., and Thomas, R.F. (1995). The Macquarie Marshes in arid Australia and their waterbirds: A 50 year history of decline. *Environmental Management,* 19, 867-878.

Kuchling, G. and Dejose, J.P. (1988). A captive breeding operation to rescue the critically endangered Western Swamp Tortoise *Pseudemydura umbrina* from extinction. *International Zoo Yearbook,* 31, 103-109.

Kuchling, G, Dejose, J.P. Burbidge, A.A, and Bradshaw, S.D. (1991). Beyond captive breeding: the Western Swamp Tortoise *Pseudemydura umbrina* recovery programme. *International Zoo Yearbook,* 31, 37-41.

Lemly, A. D., Kingsford, R.T., and Thompson, J.R. (2000). Irrigated agriculture and wildlife conservation: conflict on a global scale. *Environmental Management*, 25, 485-512.

Ligon, D.B. and Peterson, C.C. (2002). Physiological and behavioral variation in estivation in mud turtles (*Kinosternon* spp.). *Physiological and Biochemical Zoology*, 75, 283-293.

Moll, D. and Moll, E.O. (2004). *The Ecology, Exploitation, and Conservation of River Turtles.* Oxford University Press, New York.

Parmenter, C.J. (1976). The natural history of the Australian freshwater turtle *Chelodina longicollis* Shaw (Testudinata, Chelidae). PhD Thesis, University of New England.

Priest, T. (1997). Bimodal respiration and dive behaviour of the Fitzroy River Turtle, *Rheodytes leukops*. Honours Thesis, University of Queensland.

Quilty, P.G. (1994.) The background: 144 million years of paleoclimate and paleogeography. In *History of the Australian Vegetation, Cretaceous to Present* (pp. 14-44). R. Hill (Ed.). Cambridge: Cambridge University Press.

Rees, M. (2008). Impacts of urbanization on the eastern long-necked turtle *Chelodina longicollis* (Testudines:Chelidae). Honours thesis, University of Canberra.

Roe, J.H. (2007). The terrestrial ecology of a freshwater turtle, *Chelodina longicollis*, in Booderee National Park, Australia. PhD Thesis, University of Canberra.

Roe, J.H., and Georges, A. (2007). Heterogeneous wetland complexes, buffer zones, and travel corridors: landscape management for freshwater reptiles. *Biological Conservation,* 135, 67-76.

Roe, J.H., and Georges, A. (2008). Maintenance of variable responses for coping with wetland drying in freshwater turtles. *Ecology,* 89, 485-494.

Roe, J.H., Georges, A., and Green, B. (2008). Energy and water flux during terrestrial aestivation and overland movement in a freshwater turtle. *Physiological and Biochemical Zoology*, 81, 570-583.

Rogers, L.J. (1966). The nitrogen excretion of *Chelodina longicollis* under conditions of hydration and dehydration. *Comparative Biochemistry and Physiology,* 18, 249-260.

Roshier, D. A., Whetton, P.H., Allan, R.J., and Robertson, A.I. (2001). Distribution and persistence of temporary wetland habitats in arid Australia in relation to climate. *Austral Ecology,* 26, 371-384.

Spencer, R.J. (2002). Experimentally testing nest site selection: fitness tradeoffs and predation risk in turtles. *Ecology,* 83, 2136-2144.

Stott, P. (1987). Terrestrial movements of the freshwater tortoise *Chelodina longicollis* Shaw as monitored with a spool tracking device. *Australian Wildlife Research,* 14, 59-567.

Thomson, S., Kennett, R., and Georges, A. (2000). A new species of long-necked turtle (Testudines: Chelidae) from the Arnhem Land plateau, Northern Territory, Australia. *Chelonian Conservation and Biology,* 3, 675-685.

Tucker, A. D., Limpus, C. J., Priest, T.E., Cay, J., Glen, C., and. Guarino, E. (2001). Home ranges of Fitzroy River turtles (*Rheodytes leukops*) overlap riffle zones: potential concerns related to river regulation. *Biological Conservation,* 102, 171-181.

Webb, G., D., Choquenot, D., and Whitehead, P. (1986). Nest, eggs and embryonic development of *Carettochelys insculpta* (Chelonia: Carettochelidae) from Northern Australia. *Journal of Zoology, London (B) 1*, 521-550.

Wilhite, D. A. and Glantz, M. H. (1985). Understanding the drought phenomenon: the role of definitions. *Water International,* 10, 111-120.

Williams, E.E. (1953a). Fossils and the distribution of Chelyid turtles (2). Breviora *(Museum of Comparative Zoology),* 13, 1-8.

Williams, E.E. (1953b). Fossils and the distribution of Chelyid turtles (2). Breviora *(Museum of Comparative Zoology)*, 32, 1-6.

Withers, P.C. (1993). Metabolic depression during estivation in the Australian frogs Neobatrachus and Cyclorana. *Australian Journal of Zoology,* 41, 467-473.