



Does the availability of shade limit use of waterholes by desert birds?

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Table of Contents

Abstract.....	4
Plagiarism declaration.....	6
Acknowledgements.....	7
Introduction.....	9
Methods.....	18
Results.....	26
Discussion.....	45
References.....	54
Appendices	
Appendix A.....	64
Appendix B.....	66
Appendix C.....	67
Appendix D.....	71
Appendix E.....	74

Abstract

Climate change poses a major threat to living organisms, with maximum temperatures expected to continue to rise over the next few decades. Hot desert environments are particularly at risk because they experience high environmental temperatures, scarce vegetation, low productivity and unpredictable water sources. Endotherms such as birds face the challenge of maintaining a stable body temperature while avoiding dehydration. This study was carried out in the southern Kalahari, in South Africa's Northern Cape, where about 50% of bird species (36 species) depend on free-standing drinking water. Livestock farms within this area provide artificial water points, which benefit birds as well as livestock. This study determined the role of shade and cover in the use of these artificial water points by birds. An experiment was conducted at six waterholes using the Before-After, Control-Impact (BACI) design. After an initial baseline was established, three waterholes were shaded while the other three were left unshaded. Camera traps were used to record the pattern and intensity of water use by bird species at different times of the day and at varying air temperatures.

A total of 36 bird species drank at the waterholes, but data analysis was confined to the ten most abundant species. Of the ten, six species responded to the presence of shade/cover, with four species reacting positively (Cape Glossy Starling *Lamprotornis nitens*, Red-headed Finch *Amadina erythrocephala*, Black-throated Canary *Serinus atrogularis*, and Laughing Dove *Spilopelia senegalensis*), four showing no significant change in drinking patterns, and two showing a decrease in visitor numbers when the site was shaded (Cape Turtle-Dove *Streptopelia capicola*, Namaqua Dove *Oena capensis*). This suggests that providing shade at waterholes is not a universal solution to the problem of increasing heat stress experienced by birds coming to

drink. Certain species such as the Laughing Doves and Cape Turtle-Doves avoided waterholes during the warmest time of the day while the Namaqua Doves were frequent visitors at this time. However, the Laughing Dove took advantage of the shade provided at midday (warmest temperatures) as their numbers increased. The Red-headed Finch and Black-throated Canary also increased at waterholes with temperature irrespective of the time of day. These patterns imply that the provision of shade modifies the behavior of some bird species in response to predation risk or heat stress. These species utilized shade at different times of day and with varying intensities as temperatures rose.

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Introduction

Climate change poses a major threat to organisms and ecosystems with global temperatures predicted to continue rising rapidly over the coming decades (Hoffman 2010). The impact of this warming will not only result in record extreme temperatures, but average temperatures will also increase (IPCC 2011). General circulation models predict increases in maximum temperatures and frequency, intensity and duration of heat waves (IPCC 2011). Climate change is also associated with increasingly severe weather conditions such as droughts and floods (Kusangaya et al. 2014). Human activities such as urbanization, deforestation and industrialization have also played a major role in accelerating climate change (Trenberth et al. 2007). Africa has been regarded as a continent susceptible to climate change (Callaway 2004), with average temperatures expected to increase by 0.02°C per year in southern Africa (Morishima and Akasaka 2010). The southern Kalahari and surrounding areas in north-western South Africa are undergoing the fastest rates of warming compared to other regions of the country, potentially leading to a negative impact on biodiversity due to the increase in evaporation rates and rising temperatures (Kruger and Sekele 2012).

Climate change has led to major range shifts (Hughes 2000; Wuethrich 2000; McCarty 2001; Ottersen et al. 2001; Walther et al. 2001) and increased extinction risk for many organisms globally (Chown et al. 2010). High environmental temperatures have had major impacts on species geographical distributions (Hughes 2000; Wuethrick 2000; McCarty 2001; Ottersen et al. 2001; Walther et al. 2001). The factors influencing the movement of species are complex. Range shifts do not necessarily occur due to gradual changes observed within the environment but could be due to episodic events (Walther et al. 2001). However species also move in search of food,

water and habitats suitable for reproduction (Walther et al. 2002). Water resources are expected to be most impacted due to increasing evaporation rates, with decreases in the amount of run-off, soil moisture content and the availability of groundwater (Gleick 1989; IPCC 2007). Research efforts in this field have focused on modelling future changes and expected consequences (Chown et al. 2010) in order to tackle this dilemma.

Water regulation in endotherms

The performance of biochemical and organismal systems depends a great deal on temperature (Boyles et al. 2011). Endotherms, such as mammals and birds, possess the ability to maintain a stable body temperature through metabolic processes. All endotherms (animals that can regulate their body temperatures) have a range of environmental temperatures within which the metabolic costs of maintaining a stable body temperature are minimized, the thermo-neutral zone (TNZ). Birds as well as mammal body temperatures vary among and within species (Geiser and Ruf 1995; McKechnie and Lovegrove 2002). When active, birds can attain mean body temperatures ranging from 36-45°C (Prinzinger et al. 1991). Endotherms have to expend energy when the environmental temperature falls outside the TNZ (McNab 2002; Kronfeld-Schor and Dayan 2013). Water plays a key role in regulating body temperature when environmental temperatures approach or exceed body temperature (Boyles et al. 2011). Above the TNZ, endotherms can reduce their heat burden through changes in location (microhabitat), posture and behaviour. However, once environmental temperatures approach or exceed body temperature, they rely heavily on evaporative water loss to regulate heat loss, increasing the demand for water and risking dehydration, which impairs performance and can result in death (Calder and King 1974; Tieleman and Williams 1999). Evaporative water loss is particularly crucial for terrestrial organisms that have limited access to external water sources. Therefore in hot arid environments

animals try to balance thermoregulation and hydration. In dealing with this dehydrated mammals and birds allow body temperatures to rise (Angilleta et al. 2010). For instance by waiting twice as long before panting began, Emus (*Dromaius novaehollandiae*) conserved body water by avoiding evaporative cooling when dehydrated at air temperatures of about 45°C. Brain cooling is another strategy endotherms can use to tolerate elevated body temperatures when dehydrated. This strategy stops the brain from acting on mechanisms associated with evaporative cooling allowing body temperature to continue rising while preventing water loss (Mitchell et al. 2002). It has been noted in sheep where those dehydrated and involved in brain cooling attained higher body temperatures than hydrated individuals (Fuller et al. 2007). Although all these strategies help endotherms to deal with high temperatures, there are physiological constraints on the upper temperature limits endotherms can tolerate (Boyles et al. 2011). Therefore, it is a challenge for endotherms to be able to adapt and adjust body processes due to environmental changes fueled by climate change.

Most birds and mammals are endotherms that can reduce their energy expenditure in the face of harsh environmental conditions (Geiser and Ruf 1995; McKechnie and Lovegrove 2002). Surface area to volume ratios generally increase with decreasing body size, which is of advantage and efficient for individuals with a larger surface area to volume ratio in releasing heat passively and therefore are less at risk of dehydration (Geiser 2004). Amongst endotherms, birds tend to maintain higher body temperatures and mass-specific metabolic rates than mammals (McNab 1970). Birds inhabiting desert environments benefit from facultative (adaptive) hyperthermia (Tieleman and Williams 1999). This is a situation whereby their body temperatures increase by 2–4°C above normal to reduce the rate of evaporative water loss (Tieleman and Williams 1999). This process also facilitates the passive loss of heat through radiation and convection (Calder and

King 1974; Tieleman and Williams 1999). Hyperthermia could be advantageous where birds retain heat within their body tissues and only release it when environmental conditions improve through non-evaporative ways (Bartholomew and Dawson 1968; Calder and King 1974).

Birds make use of cutaneous and respiratory water loss as mechanisms for evaporative cooling, but the importance of these pathways varies among taxa (McKechnie and Wolf 2004). Cutaneous evaporation involving loss of water through the skin commonly utilized by Columbiformes (McKechnie and Wolf 2004) plays an important role in dealing with heat stress than previously thought (Webster and King 1987). While respiratory evaporation includes heat dissipation behaviours such as panting and gular fluttering. Panting, which is common in Passeriformes, enhances evaporative water loss and allows the birds to cool down faster through increased respiratory ventilation (Robertshaw 2006) in the buccal cavity and trachea of pigeons (Ramirez and Bernstein 1976) and flamingos (Bech et al. 1979). Gular fluttering uses rapid movements of the gular pouch within the throat to enhance heat loss (Robertshaw 2006). These behaviours may occur at mild to warm temperatures (30-40°C), usually below a bird's body temperature (Webster and King 1987; Powers 1992). Evaporative heat dissipation is affected by the humidity of the atmosphere (Lasiewski et al. 1966; Webster and King 1987; Powers 1992; Gerson et al. 2014). Evaporative cooling is less suitable for birds faced with the challenge of increasing air temperatures on cloudy days prior to rain, when there is high moisture content within the atmosphere as compared to clear, sunny and cloudless days (Lovegrove 2000). High humidity reduces the efficiency of heat lost through evaporation (Calder and King 1974; Weathers 1997).

Vulnerability of birds to high temperatures

Birds, because of their small body size, predominantly diurnal habits and limited use of thermally buffered microsites, are particularly vulnerable to extreme heat waves (Wolf and Walsberg 1996). When air temperatures exceed their body temperature, even inactive small birds in shaded microsites can experience rates of evaporative water loss exceeding 5% of body mass per hour (Wolf and Walsberg 1996), rapidly exceeding their limits of dehydration tolerance. Under these conditions, birds have insufficient water to maintain body temperatures below lethal limits. As a result, extremely hot weather events occasionally lead to high avian mortality rates (McKechnie and Wolf 2010). Increasing body temperatures alter enzyme activity (Daniel et al. 2010), damage mitochondrial membranes, affect other organelle functions, and decrease adenosine triphosphate (ATP) production (Abele et al. 2002), thereby starving body cells, reducing an individual's lifespan and decreasing fitness (Monaghan et al. 2009). In 2009, thousands of birds died near Carnarvon in Western Australia during a severe heat wave (Towie 2009). Numbers of endangered Carnaby's Black Cockatoos (*Calyptorhynchus latirostris*) have continued to decline due to intense heat waves and associated severe hail storms, which led to injuries, multi-organ hemorrhage and ultimately death (Saunders et al. 2011). These extreme events also lead to alterations in demographic structures and genetic diversity, affect species within populations and deaths which may affect different age classes. Birds are not the only taxa vulnerable to extreme temperature events, bats (only mammals capable of flying) face similar challenges. For example a greater number of tropical black flying foxes *Pteropus Alecto* (10 – 13%) died than temperate gray-headed foxes *Pteropus poliocephalus* (< 1%) exposed to similar high air temperatures with a higher mortality in young and adult females than in adult males

(Welbergen et al. 2008). This implies that both sub-species have varying abilities in coping with high air temperatures.

Challenges faced by birds relying on preformed water

Desert birds show considerable interspecific variation in their drinking requirements, and a large proportion (60–70%) of species in Australian and Namib desert bird communities are considered to be independent of free water, either being never observed drinking water or only visiting water resources occasionally (Fisher et al. 1972). In the Kalahari, 50% of the bird community (36 bird species) seldom drinks, although a few of these species visit waterholes on days when maximum temperatures were about 37°C (Smit 2013), suggesting that they may have been pushed close to their thermal limits. Species that seldom if ever drink free-standing water rely largely on their diets to supply them with pre-formed water (Smit 2013). In the Americas for example, White-winged Doves (*Zenaida asiatica*) feed on water-rich saguaro cactus (*Carnegiea gigantea*) fruit in mid-summer, which serves as a major source of water (Wolf et al. 2002). Other species feed on water-rich prey such as insects, other birds or small mammals (Labuschagne 1959). Alternatively, oxidative water is available to birds feeding on low-water content diets such as seeds e.g. Dune Larks *Calendulauda erythrochlamys* in the Namib Desert (Williams 1999; 2001). In most cases the oxidative water gained exceeds the amount lost through evaporation (Williams 1999). Limited food resources often force desert birds to forage during hot weather conditions (Tieleman and Williams 2002), posing the potential risk of water and energy expenditure rates exceeding intake rates (du Plessis et al. 2012). This can result in a serious threat of dehydration, especially because increasing environmental temperatures can interfere with foraging activities. For instance foraging efficiency by Southern Pied Babblers (*Turdoides bicolor*) is reduced on hot days (~ 35.5°C), resulting in their inability to obtain enough food to

compensate for body mass loss overnight (du Plessis et al. 2012). White-browed Sparrowweavers (*Plocepasser mahali*) forage less often at temperatures above 40°C, resulting in low water consumption (Smit 2013). At such air temperatures these birds may be forced to drink free-standing water to compensate for water lost via evaporation which cannot be offset due to reduced foraging activities (Smit 2013).

Temperature dependency of birds on free-standing water

The presence of free-standing water in desert habitats could therefore be an important determinant of local avian community structure and diversity. For example, proximity to waterholes could play a major role in increasing the numbers of resident species that rely on drinking water in the Kalahari. At Tswalu Game Reserve in the southern Kalahari, South Africa, Smit (2013) reported that regular drinkers did not increase frequency of visits when daily air temperatures rose, contrasting with what Fisher et al. (1972) found in Australia. A possible explanation for this discrepancy observed by Williams and Koenig (1980) could be that at high environmental temperatures frequent drinkers such as Laughing Doves (*Spilopelia senegalensis*), Cape Turtle-Doves (*Streptopelia capicola*) and Namaqua Doves (*Oena capensis*) drank more water during a single visit rather than increasing the number of visits to avoid expending more energy (Smit 2013).

Trade-offs involved in accessing scarce water resources at unshaded microsites

At high ambient temperatures, when bird activity levels such as food consumption become low (Seibert 1949) and evaporative water loss increases (Wolf and Walsberg 1996), some birds may need to visit water sources to maintain a hydrated state and in doing so they are faced with tradeoffs (McKechnie et al. 2012). Some birds, for example sandgrouse (*Pterocles* spp.), fly

great distances to drink, increasing energy expenditure and facing the risk of their body temperature reaching lethal limits (Hudson and Bernstein 1981). Significant amounts of water just obtained from surface water could be lost when embarking on a return flight under hot weather conditions (Smit 2013). In addition, the risk of predation is high at isolated free-standing water surfaces because birds can be easily spotted by their predators (Cade 1965). Foraging within shaded habitats served as cover from predators while birds felt insecure even at open sites closer to shelter (Molokwu et al. 2010). Birds visiting water sources or foraging grounds shaded by vegetation are expected to experience lower environmental temperatures and reduced metabolic costs (Molokwu et al. 2010) as opposed to those located in the sun (Smit 2013). The type of shade could also influence the amount of sun that would be blocked. Provision of shade at waterholes could therefore be important under climate change because temperatures are expected to keep rising. Direct hyperthermia associated with reduced performance could lead to more deaths in birds than dehydration as observed by Finlayson (1932) where thousands of birds were found dead around a waterhole unable to drink after an extreme heat wave (~ 49°C). Therefore at shaded waterholes the tradeoff between dehydration and hyperthermia could be greatly reduced during intense heat waves (McKechnie et al. 2012).

Aim of study

This study assessed whether the use of artificial water points by Kalahari birds was limited by the availability of shade, by experimentally providing shade at some waterholes. It also assessed whether some bird species only drank once shade was provided. The outcome of this study will help in making conservation management aware of birds within this community at risk due to rising environmental temperatures driven by climate change as well as seeking solutions to assist certain bird species. This can be achieved by noting which species are highly dependent on free-

standing water surfaces when temperatures get hotter and how they respond to shade. This study first examined patterns of water use by Kalahari bird species in terms of which species drank and when they drank in relation to time of day and temperature. Secondly, it evaluated the effect of experimental shading on patterns of water use by bird species in the Kalahari.

Research question

Does the availability of shade influence the pattern of waterhole use by birds at different environmental temperatures?

- Does shade influence bird behavior to perceived predation risk?
- Does shade influence the intensity of waterhole use during heat stress?

In order to avoid dehydration during very hot weather, birds reliant on open water sources must drink. However, there is no shade at most water sources available in the Kalahari, so birds are exposed to high environmental temperatures in the full sun and predation risk while drinking. Birds must therefore make a trade-off between avoiding dehydration and avoiding hyperthermia and predation.

Methods

Study Area

The study took place during October and November 2014 at Farm Murray (26° 59'S, 20° 52'E) in the southern Kalahari Desert, Northern Cape, South Africa (Figure 1). This is a semi-desert region with maximum air temperatures of over 40°C and average air temperatures of about 35°C usually higher than most of southern Africa during summer (October – April; Kruger and Shongwe 2004). The area is characterized by sparse, arid savannas on deep red sands and immobile dunes with a relatively low relief in comparison to other parts within the country (Perkins and Thomas 1993). Rainfall is erratic and unpredictable with 100-400 mm per year occurring predominantly during summer (Lovegrove 1993). The vegetation consists of grasses (*Stipagrostis amabilis*), scattered shrubs (*Rhigozum trichotomum*) and woody cover (*Vachellia erioloba*, *Senegalia mellifera*, *V. haematoxylin*, *Boscia albitrunca*; Palmer and van Rooyen 1998). The significant presence of woody cover is as a result of a dry river bed (the Kuruman River) at the northern boundary of the farm, which supplies underground water. Farm Murray conducts pastoral agriculture with sheep and cattle as well as game hunting. The six experimental sites (Figure 1) selected were located on the farm within dune streets with waterholes usually made out of plastics or metal. The six waterholes were chosen based on those accessible while others were restricted, this included waterholes frequently utilized by cattle as they could pull down wooden frames and destroy cameras. In spite of this, it was ensured that each one represented the community of birds in those areas on Farm Murray while avoiding an overlap where two or more waterholes were within close distances as shown below.

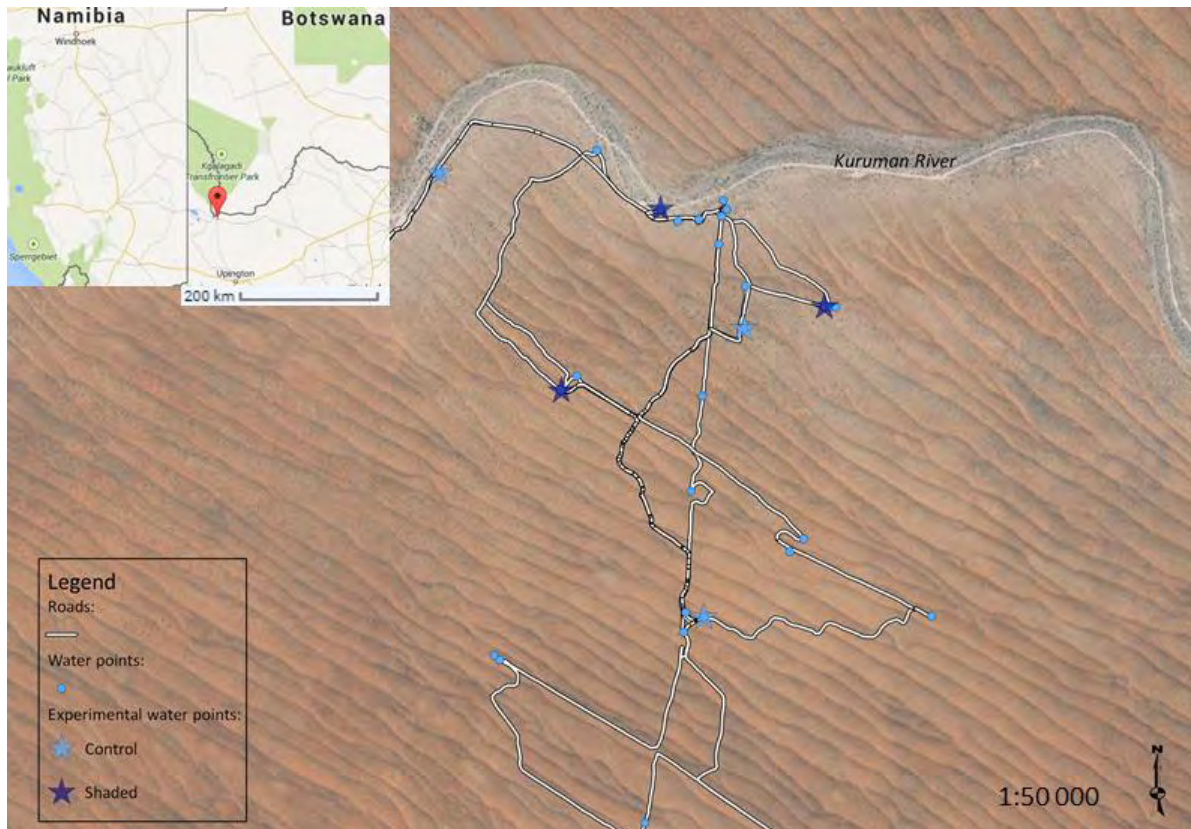


Figure 1: The study site is bordered by Kgalagadi Transfrontier Park, Botswana and Namibia in the north and west respectively. The map of Farm Murray and surrounding land shows the shaded and unshaded waterholes. Blue circles are waterholes; dark blue stars represent the shaded waterholes (waterholes one, two and three) while the lighter blue stars signify the unshaded waterholes (waterholes four, five and six). White lines are road tracks running parallel and perpendicular to the sand dunes.

Experimental design

Data collection: Data were collected from 14 October to 8 November 2014. Air temperatures, humidity and rainfall were measured using a portable weather station (Vantage Pro2, Davis Instruments, Hayward, CA). The temperature sensor of the weather station was calibrated against a mercury thermometer (resolution 0.1°C, accuracy traceable to the South African Bureau of Standards) between a range of 5-50°C.

Experiment design: A before-after, control-impact (BACI) design was employed to test main effects and interactions between two experimental phases (before and after shading waterholes) and two treatments (troughs that stayed unshaded throughout and waterholes shaded in the second phase of the experiment; Green 1979; Stewart-Oaten et al. 1986; Skalski and Robson 1992). There were six waterholes; three experimental and three controls. The main focus of the experiment was to determine if the intensity of waterhole use by bird species is altered by providing additional shade. A secondary goal was to examine the effect of factors such as time of day and air temperature on the number of birds drinking (Box and Norman 1971). BACI is a recommended approach to help determine changes by examining both experimental phases and the shaded versus unshaded sites. This eliminates the possibility that variables not considered might influence observations (McDonald et al. 2000). In this study it separates the effect of the treatment from the background effects of changes in temperature and rainfall as the season progressed. Wooden frames were erected over six waterholes. The frames were designed to support a heavy-weight dark blue shade-cloth canopy that blocked approximately 80% of solar radiation to shade the waterholes during the hottest period of the day (12h00–16h00). The shade frames were 3 m x 2 m and raised 1.5 m above the ground (supported by poles sunk 0.5 m in the ground; Figure 2). No data were collected in the six days after the frames were erected and five days after the shade cloth were added to allow the birds to acclimatize to the frames and cloth respectively. No observations were made before the start of the experiment and little time was allocated for birds to acclimatize due to time constraint. Thereafter observations were made for 12 days excluding rainy days. From 30 October to 8 November 2014 three of the six frames were covered with the heavy-weight dark blue shade cloth (Figure 3). Experimental waterholes were chosen by examining the intensity of use by birds during the first phase of the experiment, in

terms of an overall impression of the numbers that visited each trough. This ensured that the waterholes in both control and shaded groups were normally equally well visited by birds. Therefore waterholes 1, 2 and 3 were shaded while waterholes 4, 5 and 6 were left unshaded serving as control. These waterholes were paired up on the basis of evenness in attendance (high, medium and low), waterhole orientation, surrounding vegetation and the type of birds visiting.

Data were collected using programmable, high-resolution LTL Acorn 5310WVG 940 nm MMS camera traps at each waterhole. These cameras were programmed to take pictures every minute from 6h00 until 19h00 to record the number of birds visiting. They were not set to take photos at night in order to save memory card space and battery life. Only birds perched on the edge of the waterholes were counted to avoid including birds just passing through but not intending to drink. The date and time on the camera traps were synchronized with the weather station. Five sampling periods of one hour each (6–7h00, 9–10h00, 12–13h00, 15–16h00 and 18–19h00) were chosen to maximize the range of air temperatures sampled (Figure 4).

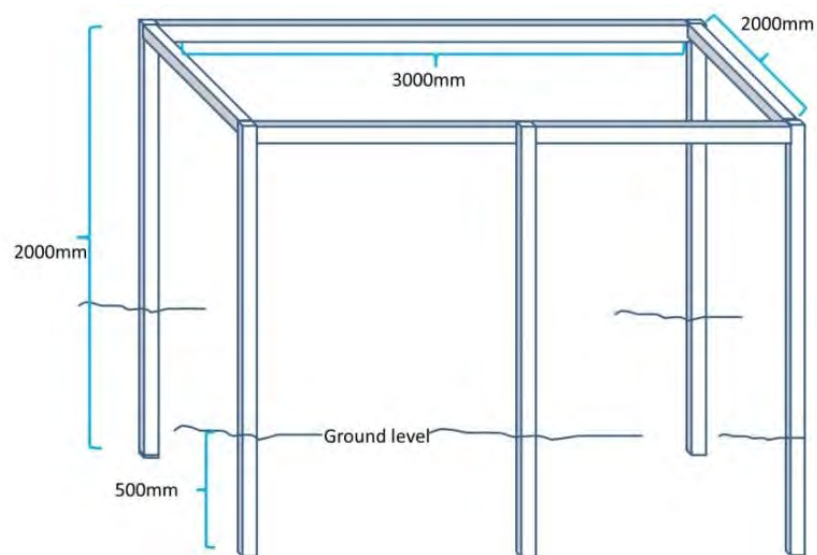


Figure 2: The dimensions of the wooden frames set up at waterholes.



Figure 3: Wooden frames over waterholes **a)** without shade and **b)** with shade.

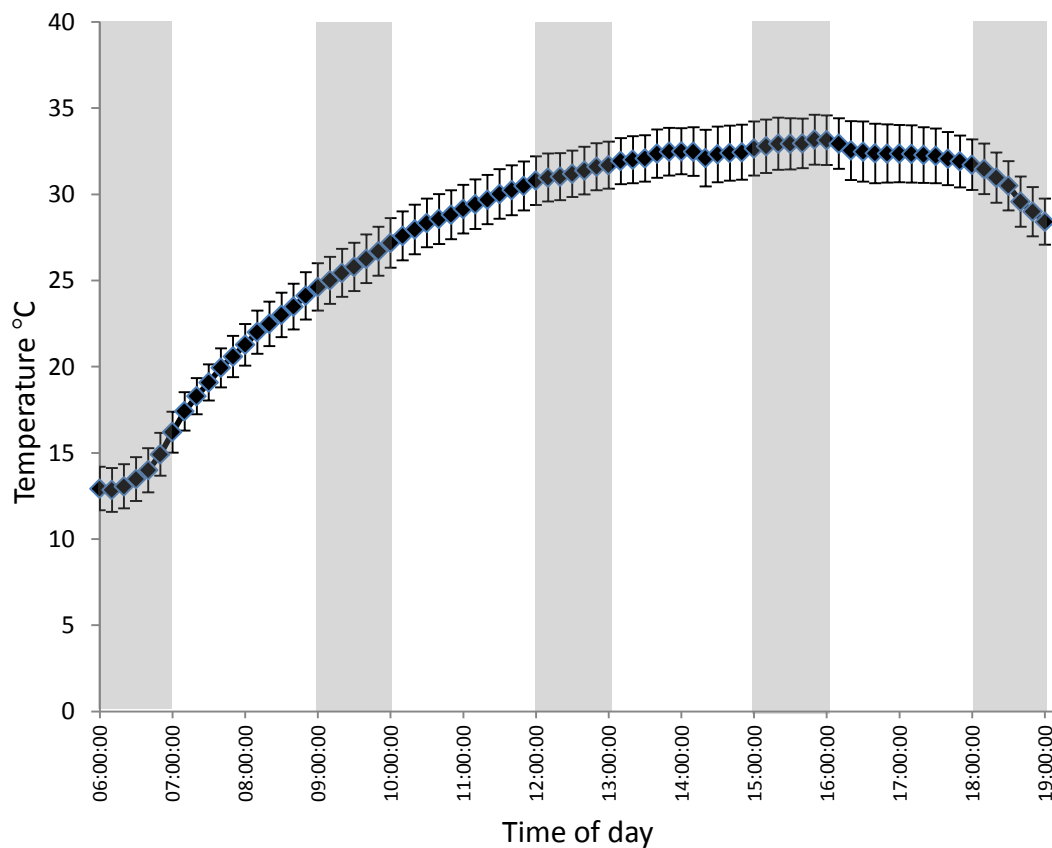


Figure 4: Average air temperature and standard error as a function of time of day over the duration of the experiment (12 days) extracted from the weather station data. The grey bars show the five sampling periods.

Statistical Analysis

All analyses were carried out in the R statistical environment (R version 0.98.1091, RStudio 2014) using the R-studio interface (R Development Core Team 2014). Results were deemed statistically significant if $p < 0.05$. Differences in mean daily temperature between the first and second phase of the experiment was assessed using a two-tailed t-test.

General patterns of water use

A Generalized Linear Model (GLM) with Poisson distribution was fitted to data collected during the initial phase of the experiment (before shading), in order to examine general patterns of water use by the abundant bird species recorded drinking. The response variable for this model was the number of birds per hour calculated by summing up the number of birds seen drinking across an entire hour. Fixed factors included time of day, temperature and waterhole identity. Model assumptions were checked by visually examining residual plots.

Effect of experimental shading on intensity of water use

A Generalized Linear Mixed-Effects Models (glmer) from the package lme4 version 1.1-7 (Bates et al. 2014) was used to assess the impact of adding artificial shade to waterhole use by birds. The intensity of waterhole use by birds was modeled as a function of experiment phase (Phase 1: before shading and Phase 2: after shades were put up at half of the waterholes), treatment group (control: waterholes that were never shaded; and shade: waterholes that were shaded in Phase 2), and the interaction between the two. Waterhole identity was treated as a random factor to allow for repeated measures and to accommodate differences between the six waterholes. A model of the number of birds per hour, assuming a Poisson error distribution, would not converge, so it

was re-run as a binomial distribution of the proportion of photos out of the 60 taken in an hour in which the species of interest were present. This variable was used as an index of the intensity of use of the waterhole by each bird species. This glmer was run on the entire dataset to examine the effect of shading on the abundant bird species as a whole, as well as on each of the 10 abundant bird species in Table 1. Each model was checked for over-dispersion, and only the model for Sociable Weavers was found to be over-dispersed. Therefore an individual-level random factor was included in this model to compensate for the over-dispersion.

To investigate patterns of waterhole use by birds in relation to temperature and time of day, and to assess whether providing shade altered these patterns of use, the data set was subset into “Phase 1” and “Phase 2” sections. Binomial models were fitted to these data, with response variable the proportion of photographs with birds present out of the 60 photographs taken per hour, while the explanatory variables included time of day, temperature, treatment and all three interaction terms. Waterhole was excluded as a random factor because it prevented the models from converging, but was instead included as a fixed factor to control for waterhole specific effects during Phase 1 of the experiment. This could be due to too few data.

Baseline patterns of water use during Phase 1 of the experiment (before shading)

To determine the pattern of use of waterholes before shading by different bird species the explanatory variables included the waterhole (wtr), time of day (h), quadratic function of time of day (h^2), temperature (T_a), and the interaction between time of day and temperature ($h*T_a$). All variables were treated as categorical except for temperature measured as a continuous variable. The dredge function in the MuMIn package version 1.12.1 performed an automated selection of models with all possible different combinations of the above variables with associated model

weights, degree of freedom, loglikelihood and AICc (Second-order Akaike Information Criterion values). Using AICc, a subset of models was chosen, including all models within 2 AICc points of the best model. From this subset, the simplest nested model (containing the smallest number of factors) was chosen as the best model, following Arnold (2010). After running the chosen models the summary included variables that were important to certain species. It is important to note the variables that influence a bird's behavior in the absence of shade.

Patterns of water use during Phase 2 of the experiment: the effects of providing shade

To determine whether providing shade altered the pattern of use of waterholes during Phase 2 of the experiment (after shading) by different bird, species the explanatory variables included the time of day (h), quadratic function of time of day (h^2), temperature (T_a), treatment (trt), interaction between time of day and temperature ($h*T_a$), interaction between temperature and treatment (T_a*trt) and finally the interaction between time of day and treatment ($h*trt$). Selection of the best model for each bird species was carried out as described above. Shading was deemed to have had an effect on bird behavior if interaction terms between treatment and time of day, and treatment and temperature were statistically significant: that is, if birds used the shaded waterholes in a different manner from the control (unshaded) waterholes, during this time period. After shading, it is important to note the variables that interact with treatment in order to identify what variable influences the use of shade.

Results

Study Species

A total of 36 bird species were recorded drinking at farm waterholes during this study. Excluding nomadic Wattled Starlings (*Creatophora cinerea*), which were present only until the end of October, the ten most abundant species found drinking at waterholes were selected for further analysis (Table 1). Drinking records for each of these species ranged from several hundreds to several thousands. Their associated body masses and diets are listed (Table 2).

Table 1: Total number of occasions on which individuals of 36 Kalahari bird species were observed drinking at shaded and control waterholes during the entire study period. Time periods were between 6-7h00, 9-10h00, 12-13h00, 15-16h00 and 18-19h00 over the 12 days during which birds were recorded drinking at the six waterholes.

Species	Instances recorded drinking
Sociable Weaver (<i>Philetairus socius</i>)	17106
Cape Turtle-Dove (<i>Streptopelia capicola</i>)	4929
Cape Glossy Starling (<i>Lamprotornis nitens</i>)	4588
Red-headed Finch (<i>Amadina erythrocephala</i>)	4558
Southern Grey-headed Sparrow (<i>Passer diffusus</i>)	4114
Laughing Dove (<i>Spilopelia senegalensis</i>)	2267
Wattled Starling (<i>Creatophora cinerea</i>)	2216
Black-throated Canary (<i>Serinus atrogularis</i>)	1077
Namaqua Dove (<i>Oena capensis</i>)	469
Violet-eared Waxbill (<i>Uraeginthus granatinus</i>)	419
White-browed Sparrow-weaver (<i>Plocepasser mahali</i>)	372
Shaft-tailed Whydah (<i>Vidua regia</i>)	328
Yellow Canary (<i>Serinus flaviventris</i>)	261
Black-cheeked Waxbill (<i>Estrilda chamosyna</i>)	196
Fork-tailed Drongo (<i>Dicrurus adsimilis</i>)	128
Kori Bustard (<i>Ardeotis kori</i>)	88
Speckled Pigeon (<i>Columba guinea</i>)	74
Gabar Goshawk (<i>Micronisus gabar</i>)	61
Southern Masked-Weaver (<i>Ploceus velatus</i>)	54
Groundscraper Thrush (<i>Psophocichla litsitsirupa</i>)	34
Red-faced Mousebird (<i>Urocolius indicus</i>)	27
Lilac-breasted Roller (<i>Coracias caudatus</i>)	24
Crowned Lapwing (<i>Vanellus coronatus</i>)	21
Cape Sparrow (<i>Passer melanurus</i>)	18
Black-chested Prinia (<i>Prinia flavicans</i>)	16
Fawn-coloured Lark (<i>Mirafra africanoides</i>)	16
Golden-tailed Woodpecker (<i>Campethera abingoni</i>)	13
Spotted Thick-knee (<i>Burhinus capensis</i>)	11
Green-winged Pytilia (<i>Pytilia melba</i>)	5
Marico Flycatcher (<i>Bradornis mariquensis</i>)	4
Red-eyed Bulbul (<i>Pycnonotus nigricans</i>)	4
Southern Pale Chanting Goshawk (<i>Melierax canorus</i>)	4
Familiar Chat (<i>Cercomela familiaris</i>)	2
Acacia Pied Barbet (<i>Tricholaema leucomelas</i>)	1
Kalahari Scrub-Robin (<i>Cercotrichas paena</i>)	1
Scaly-feathered Finch (<i>Sporopipes squamifrons</i>)	1

Table 2: Body mass and diet for the ten selected bird species (Hockey et al 2005).

Species	Body mass (g)	Diet
Sociable Weaver	27	flowers, insects
Cape Turtle-Dove	150	seeds*
Cape Glossy Starling	90	fruits, insects, nectar, meat
Red-headed Finch	24	seeds*
Southern Grey-headed Sparrow	24	seeds*
Laughing Dove	100	seeds*
Black-throated Canary	13	flowers, seeds, insects
Namaqua Dove	40	seeds*
Violet-eared Waxbill	12	seeds*
White-browed Sparrow-weaver	47	insects, seeds, fruits, leaves

* often supplement with insects, fruits or nectar.

Mean air temperatures increased from Phase 1 ($26.1 \pm 8.8^\circ\text{C}$) to Phase 2 ($29.4 \pm 6.8^\circ\text{C}$, $t = -11.9$, $p < 0.001$), but maximum temperatures were slightly higher in Phase 1 ($39.0 \pm 8.8^\circ\text{C}$) than Phase 2 ($37.7 \pm 6.8^\circ\text{C}$). Rainfall was only recorded during Phase 2 adding up to 9.1 mm. The amount was considerate with the highest rainfall event of 2.03 mm. The Green-winged Pytilia (*Pytilia melba*), Kalahari Scrub-Robin (*Cercotrichas paena*), African Red-eyed Bulbul (*Pycnonotus nigricans*), Scaly-feathered Finch (*Sporopipes squamifrons*) and Southern Pale Chanting Goshawk (*Melierax canorus*) were only present during phase 2. However, the African Red-eyed Bulbul was the only bird among these that visited a shaded waterhole (WH2). This bird occurs in the dry regions of Western South Africa and is likely restricted to areas where water and fruit-bearing trees are readily available and therefore less tolerant of aridity, as the only waterhole (2) it was sighted falls within 300 m to household gardens (Lloyd and Palmer 1998).

Examining general patterns of water use by birds on Farm Murray

Bird visitations differed across waterholes with similarities observed between some waterholes. Although the effect of temperature was significant, the effect size was small and negative with bird numbers per hour. Visits pooled for the six waterholes decreased with increasing temperature (Table 3). There was a significant difference (intercept) in bird numbers when waterhole 1 was compared with waterholes 2, 3, 4, 5 and 6 (Table 3) with waterhole 1 not significantly different from waterhole 6.

Table 3: A general pattern of waterhole use by the 10 abundant bird species. Model included variables: intercept (waterhole 1) time of day, air temperature, and waterholes 2, 3, 4, 6 and 8. Family=Poisson.

	Estimate	Std. Error	z value	P-value
(Intercept)	6.77	0.29	23	< 0.001 ***
Time of day	-0.01	0.09	-0.10	0.92
Temperature	-0.04	0.02	-2.26	0.02 *
Waterhole 2	-1.36	0.13	-10.36	< 0.001 ***
Waterhole 3	-1.23	0.10	-12.31	< 0.001 ***
Waterhole 4	-1.60	0.19	-8.31	< 0.001 ***
Waterhole 5	-1.27	0.13	-10.01	< 0.001 ***
Waterhole 6	-0.13	0.09	-1.46	0.143

***= extremely significant ($p < 0.001$), **= very significant ($0.01 > p > 0.001$), *= significant ($0.1 > p > 0.01$) and . =near significant ($p < 0.1$)

The pattern of drinking in birds per hour before shading displays an increase from 9-10h00, and a decrease at about midday (12-13h00) and late in the evening (18-19h00, Figure 5). Drinking rates were highest at waterholes (WH) 1 and 5 and lowest at WH 2 and 6. An intermediate number of birds were recorded at WH 3 and 4. Accordingly waterholes not significantly different were paired up except for WH 3 and 4 (Table 4).

Table 4: A matrix showing similarities and differences between the six waterholes in terms of the number of birds recorded drinking at each waterhole. Each waterhole was reordered as a reference level to serve as an intercept and compared with the other five. Pair of waterholes not significantly different from one another is represented with a small bold letter (**n**) and significantly different waterholes presented in a small letter (s).

	WH1*	WH2*	WH3*	WH4°	WH5°	WH6°
WH1*		s	s	n	n	s
WH2*	s		n	s	s	n
WH3*	s	n		s	s	n
WH4°	n	s	s		s	s
WH5°	n	s	s	s		s
WH6°	s	n	n	s	s	

* = shaded ° = unshaded (control) **n** = not significantly different ($p > 0.05$), s = significantly different ($p < 0.05$).

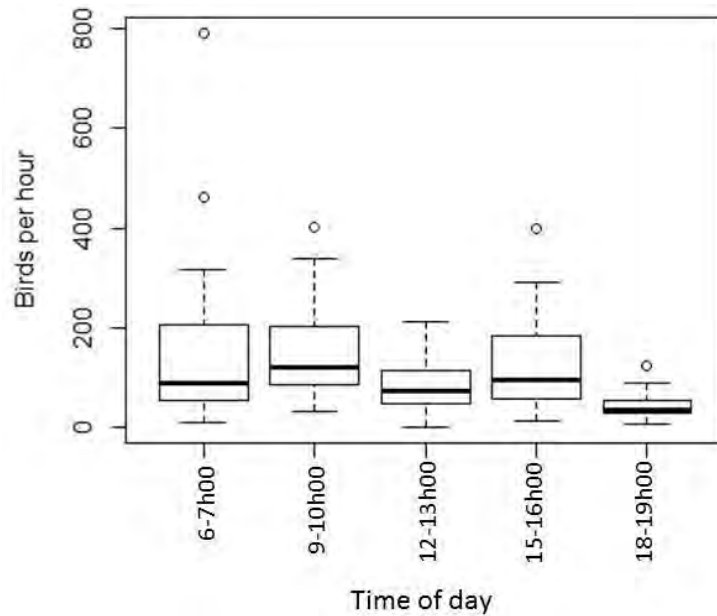


Figure 5: Total number of birds present per hour before shading at the six waterholes.

Effect of experimental shading on the general pattern of waterhole use by birds

Both control and shaded waterholes showed a reduction in intensity of use by birds in Phase 2 of the experiment (after shade was added to WH 1, 2 and 3; Table 5), but this reduction was greater for shaded waterholes (Figure 6).

Table 5: Interactions between the experimental phase (exp; two levels ‘1’ [Before] and ‘2’ [After]) and treatment group (shade and control [unshaded]) on the general drinking pattern of the abundant bird species.

	Estimate	Std. Error	z value	P-value
(Intercept)	-2.03	0.11	-18.772	< 0.001 ***
treatment: shade^control	-0.22	0.15	-1.466	0.14
exp: phase1^phase2	0.10	0.02	4.569	< 0.001 ***
treatment^exp	0.09	0.03	2.971	0.003 **

^ = interaction.

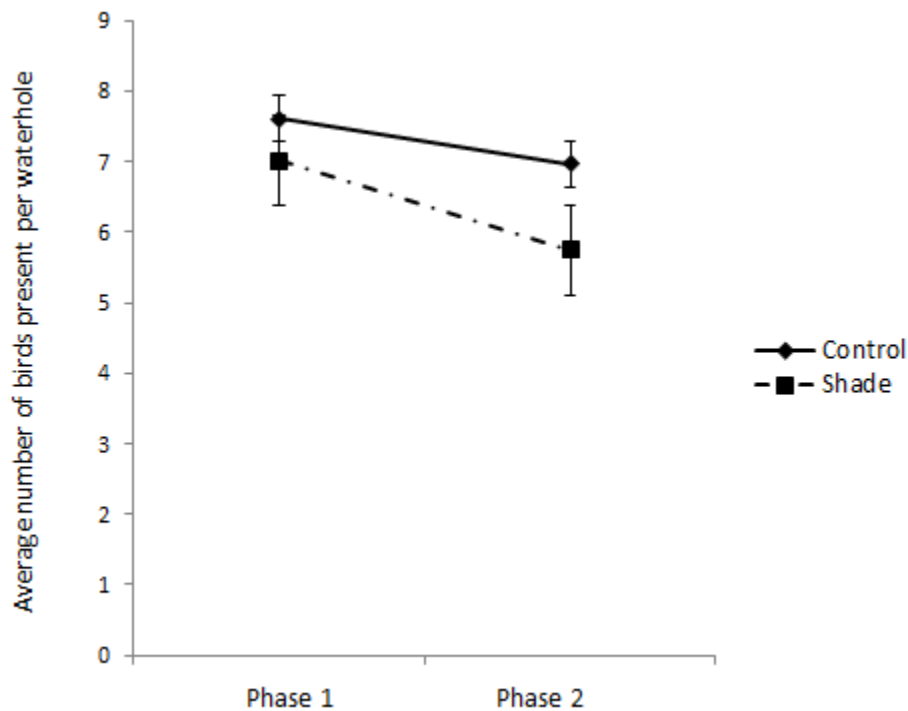


Figure 6: The interaction between the experimental phase (‘1’ and ‘2’) and treatment group (shaded or control) on the average number of birds visiting waterholes. Bars represent standard error.

Six of the ten most abundant species responded significantly to the addition of shade (Table 6 selected from Appendix A), with Cape Glossy Starlings, Red-headed Finches, Black-throated Canaries and Laughing Doves all increasing their use of shaded waterholes compared to control

waterholes, whereas numbers of Cape Turtle-Doves and Namaqua Doves decreased at shaded sites (Figure 7). Others namely Sociable Weaver, Southern Grey-headed Sparrow, White-browed Sparrow-weaver and Violet-eared Waxbill did not respond to the presence of shade.

Out of the 36 bird species (aside from the 10 analyzed) in Table 1 sighted drinking in significant numbers only the Yellow Canary increased after the provision of shade, others either did not respond or decreased in number.

Table 6: Models accounting for the interaction effect between the treatments (control and shade) and experimental phases (phase 1 and phase 2) for 10 selected species below showing their estimates, standard errors, z values and P values. Family= Binomial.

Species	Estimate	Std. Error	z value	P-value
Sociable Weaver	0.44	0.27	1.62	0.11
Cape Turtle-Dove	1.02	0.08	12.08	< 0.001 ***
Cape Glossy Starling	-0.36	0.09	-3.90	< 0.001 ***
Southern Grey-headed Sparrow	0.16	0.10	1.54	0.12
Red-headed Finch	-0.59	0.10	-6.12	<0.001 ***
Black-throated Canary	-0.43	0.25	-1.74	0.08 .
Namaqua Dove	0.37	0.22	1.69	0.09 .
Laughing Dove	-0.19	0.11	-1.73	0.084 .
Violet-eared Waxbill	-0.19	0.25	-0.76	0.45
White-browed Sparrow-weaver	0.32	0.27	1.21	0.23

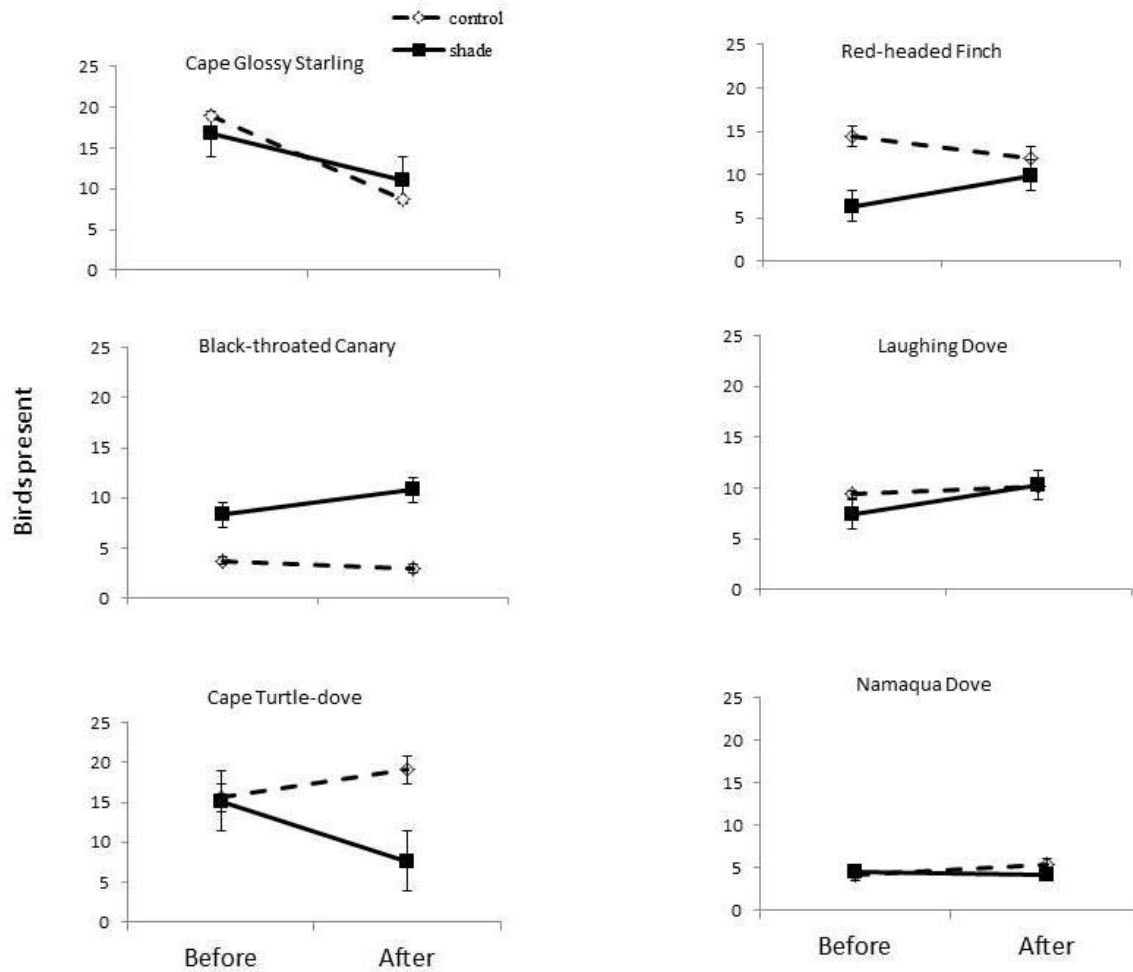


Figure 7: Interactions between experimental phase (Phase 1: before shading ‘Before’; Phase 2: after shading ‘After’) and treatment group (waterholes shaded in Phase 2; vs. control waterholes [never shaded]) for six species. Data presents the average number of birds present drinking at waterholes through-out the experiment. Bars represent standard errors.

Baseline patterns of water use during Phase 1 of the experiment (before shading)

Overall there was no significant interaction between time of day and temperature for the abundant bird species when I tested for a general pattern of water use during the first phase of the experiment. However, waterhole, temperature and time of day as independent factors had significant effects on the pattern of use by all bird species. Some individual species showed

strong interactions with temperature at different times of the day as shown below (Table 7). Each model has an AICc weight (delta in Appendix B) within a value of 2 as stated in page 25 that has a good fit to the data. The significant values presented for each species below were extracted from Appendix C.

Table 7: Best models for the 10 selected bird species during Phase 1 of the experiment. Provided is a list of variables that each species responded to significantly, these include time of day (h), quadratic function of time of day (h^2), temperature (T_a), waterhole (wtr) and the interaction between time of day and air temperature. Each species has its corresponding degrees of freedom (df), loglikelihood (LogLik), Akaike Information Criterion (AICc) and weight (Wt).

Species	Best model	df	LogLik	AICc	Wt
Sociable Weaver	$h+h^2+T_a+wtr+h*T_a$	10	-1108.32	2237.7	1.000
Cape Turtle-Dove	$h+h^2+T_a+wtr+h*T_a$	10	-879.14	1779.3	1.000
Cape Glossy Starling	$h+h^2+T_a+wtr+h*T_a$	10	-766.69	1554.6	0.999
Southern Grey-headed Sparrow	$h+T_a+wtr+h*T_a$	9	-714.97	1449.0	0.583
Red-headed Finch	$h+h^2+T_a+wtr+h*T_a$	10	-581.21	1183.6	0.790
Black-throated Canary	h^2+T_a+wtr	8	-168.60	355.4	0.383
Namaqua Dove	T_a+h^2	3	-178.65	363.6	0.165
Laughing dove	$h+T_a+wtr+h*T_a$	9	-516.28	1051.6	0.702
Violet-eared Waxbill	h^2+wtr	7	-130.04	276.1	0.290
White-browed Sparrow-weaver	T_a	2	-85.63	175.5	0.276

h = time of day, h^2 = time of day squared, T_a = air temperature, wtr= waterhole. Two variables joined by a *=interaction.

Numbers of Laughing Doves and Red-headed Finches drinking showed a very similar interaction between time of day and air temperature. The proportions of these birds drinking in the late morning (9-10h00) increased slightly as temperatures approached 30°C, and a similar pattern was found in the late afternoon (15-16h00) and evening (18-19h00). But at midday, when

temperatures approached 36°C, numbers of these birds decreased. This interaction was significant for both species (Red-headed Finch estimate = -0.03, $t = -3.96$, $p < 0.001$; Laughing Dove estimate = -0.02, $t = -2.80$, $p = 0.01$).

Large numbers of Sociable Weavers visited waterholes throughout the day, with a 20% difference in the proportion of photos at 15-16h00 when temperatures exceeded 36°C and a very negligible number recorded late in the evening (Figure 8; estimate = 0.04, $t = 4.28$, $p < 0.001$).

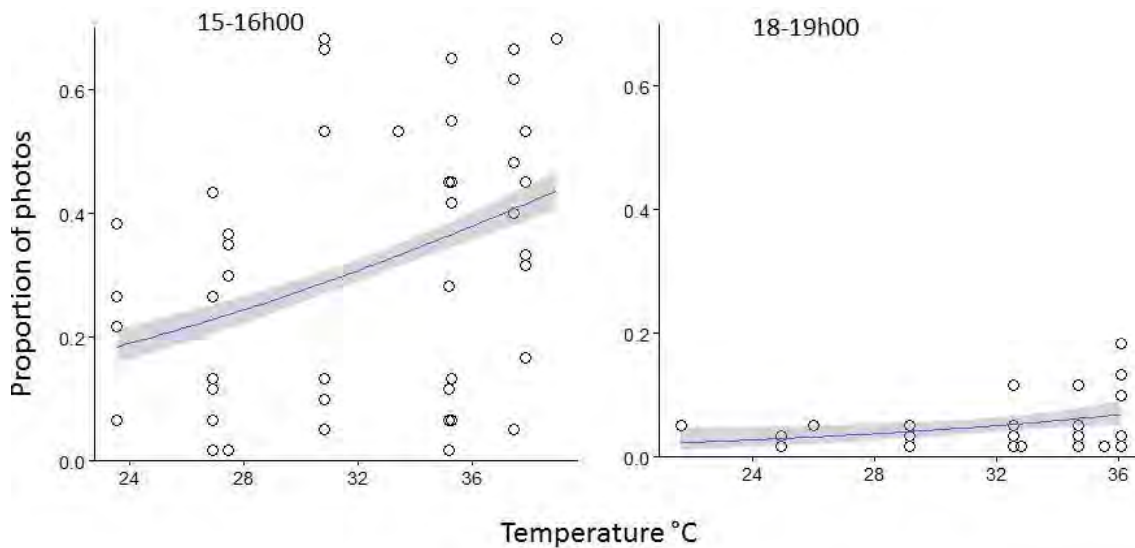


Figure 8: Proportion of photos with Sociable Weavers as a function of temperature at 15-16h00 and at 18-19h00 respectively.

Cape Glossy Starlings also increased their use of waterholes as temperatures increased. However, the rate of increase was not consistent, with the least increase in Cape Glossy Starlings with temperature late in the morning. However, Cape Glossy Starlings showed a similar trend to Sociable Weavers where the highest proportion of birds seen was late in the afternoon with increasing temperatures (estimate = 0.02, $t = 1.98$, $p = 0.05$). More Cape Turtle-Doves visited

early in the morning, as temperatures approached about 25°C. At midday, when temperatures were about 30°C, Cape Turtle-Doves recorded were relatively low. Thereafter there was a greater occurrence of Cape Turtle-Doves drinking late in the evening with warmer temperatures of about 35°C (estimate = -0.04, $t = -6.54$, $p < 0.001$)

Air temperature and the quadratic function of time of day had independent effects on the proportion of Black-throated Canaries drinking, with numbers generally increasing with temperature (estimate = 0.05, $t = 3.64$, $p < 0.001$), but with fewer numbers at midday than in the late morning and late afternoon (estimate = -0.06, $t = -3.57$, $p < 0.001$). Namaqua Doves also responded to time of day and air temperature separately, increasing with air temperature (estimate = 0.03, $t = 2.49$, $p = 0.02$) and peaking at midday (estimate = -0.23, $t = -2.32$, $p = 0.02$). Use of water by Southern Grey-headed Sparrows and Violet-eared Waxbills varied with time of day, but for Violet-eared Waxbills it was best explained by the quadratic function of temperature, with highest waterhole use in the middle of the day (estimate = -0.03, $t = -2.04$, $p = 0.05$). By contrast, few Southern Grey-headed Sparrows were recorded drinking at midday (estimate = -0.72, $t = -3.12$, $p = 0.002$). The only variable with a significant effect on use of waterholes by White-browed Sparrow-weavers was air temperature, with numbers increasing with temperature (estimate = 0.04, $t = 3.43$ and $p = 0.001$).

Patterns of waterhole use during Phase 2 of the experiment: the effects of providing shade

Addition of shade resulted in altered patterns of use of water in relation to either temperature or time of day by six of the 10 selected Kalahari bird species. Best models for these six species contained interaction terms between treatment (shaded/unshaded) and temperature (Red-headed Finch), time of day (Sociable Weaver, Cape Turtle-Dove, Southern Grey-headed Sparrow, Laughing dove) or both (Black-throated Canary) (Table 8; each model was chosen from

Appendix D). The significant values presented for each species below were extracted from Appendix E.

Table 8: Best models for the 10 selected bird species during Phase 2 of the experiment. The variables include time of day (h), quadratic function of time of day (h^2), air temperature (T_a), treatment (trt) and the interaction between time of day and temperature.

Species	Best model	df	LogLik	AICc	Wt
Sociable Weaver	$h+h^2+T_a+trt+h*T_a+h*trt$	7	-1089.16	2193.1	0.549
Cape Turtle-Dove	$h+h^2+T_a+trt+h*T_a+h*trt$	7	-605.85	1226.5	0.609
Cape Glossy Starling	$h+h^2+T_a+trt+h*T_a$	6	-465.22	943.1	0.312
Southern Grey-headed Sparrow	$h+h^2+T_a+trt+h*T_a+h*trt$	7	-471.78	958.5	0.415
Red-headed Finch	$h+h^2+T_a+trt+h*T_a+T_a*trt$	7	-590.86	1196.5	0.291
Black-throated Canary	$h+T_a+trt+h*T_a+h*trt+T_a*trt$	7	-190.36	396.4	0.398
Namaqua Dove	$h+h^2$	3	-104.52	215.5	0.124
Laughing dove	$h+h^2+T_a+trt+h*T_a+h*trt$	7	-442.49	900.1	0.524
Violet-eared Waxbill	T_a+trt	3	-113.29	233	0.113
White-browed Sparrow-weaver	T_a	2	-137.08	278.3	0.142

Sociable Weaver

Visiting rates to waterholes by Sociable Weavers continued to grow from morning until late afternoon and then dropped in the evening. Time of day and air temperatures interacted significantly for Sociable Weavers at both phases of the experiment (estimate = 0.10, $z = 4.85$, $p < 0.001$) as numbers increased during the second phase. However, this was not in response to the presence of shade (estimate = 0.44, $z = 1.62$, $p = 0.11$).

Cape Turtle-Dove

For Cape Turtle-doves, a strong negative interaction was observed between time of day and temperature. Bird numbers generally dropped as temperatures increased at midday (estimate = -0.0336, $z = -6.701$, $p < 0.001$). A significant interaction between time of day and treatment was also noted with a tremendous decrease in birds sighted at the shaded water holes particularly late in the afternoon as shown below (estimate = -0.221939, $z = -4.827$, $p < 0.001$; Figure 9).

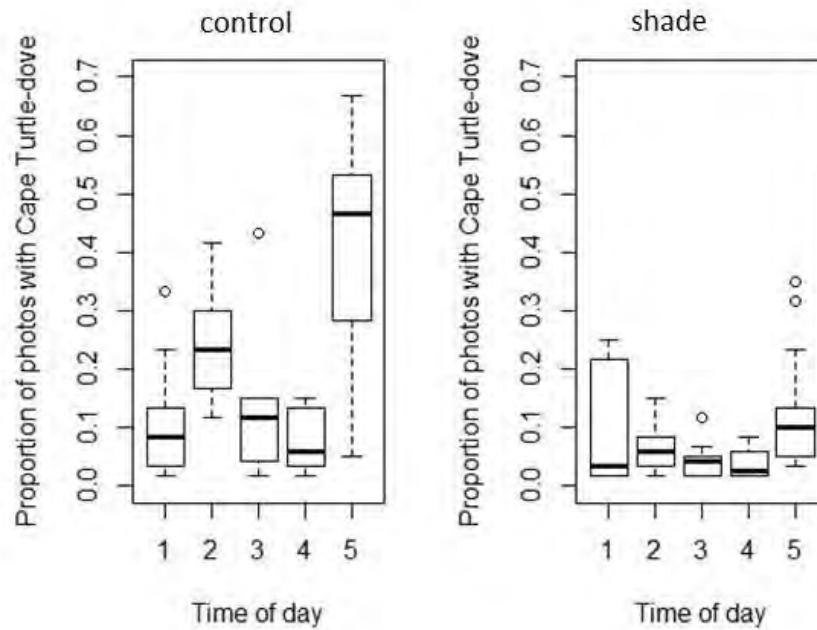


Figure 9: The proportion of photos with Cape Turtle-Doves at different times of the day at control (unshaded) and shaded waterholes (1=6-7h00, 2=9-10h00, 3=12-13h00, 4= 15-16h00 and 5= 18-19h00).

Cape Glossy Starling

More starlings were recorded at shaded than unshaded waterholes during the second phase of the experiment (estimate = 0.23, $z = 3.02$, $p = 0.003$). There was a strong, positive interaction between time of day and temperature, with numbers increasing with temperature throughout the day, but especially at noon (estimate = 0.05, $z = 5.77$, $p < 0.001$). A similar trend was noticed at experimental phase 1 but with smaller numbers of starlings visiting waterholes.

Red-headed Finch

Red-headed Finches had a significant interaction between time of day and air temperatures during phase 1 and 2 of the experiment at both shaded and unshaded waterholes. However, this interaction was less significant at phase 2 (estimate = 0.01, $z = 1.71$, $p = 0.09$) than at phase 1 (estimate = -0.03, $z = -3.96$, $p < 0.001$). The proportion of photographs per hour containing Red-headed Finches dropped as temperatures increased at unshaded (control) waterholes and increased at shaded waterholes (estimate = 0.05, $z = 4.76$, $p < 0.001$; Figure 10).

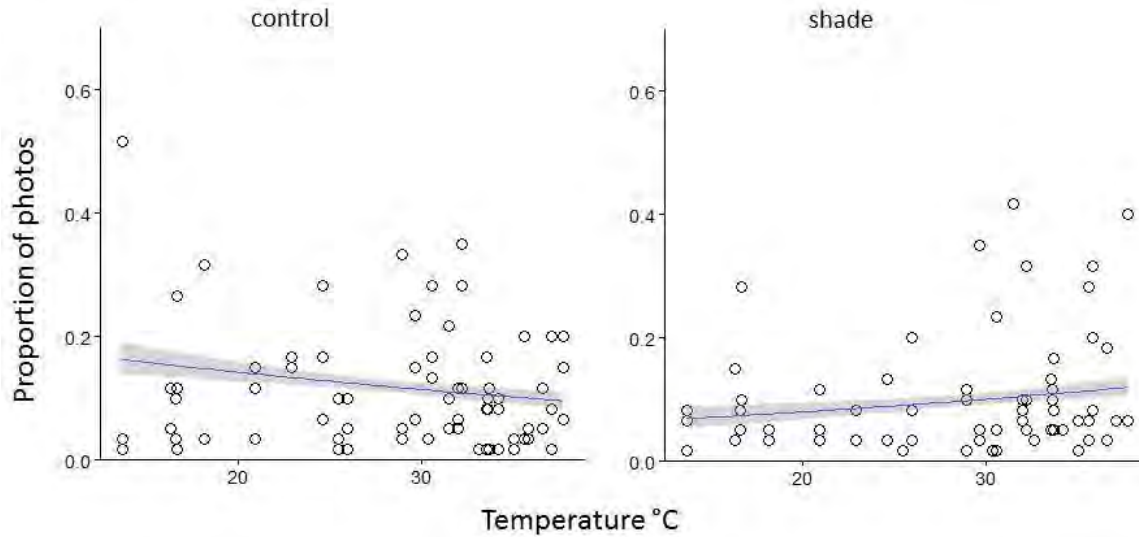


Figure 10: The proportion of photos with Red-headed Finch as a function of temperature at unshaded (control) and shaded waterholes respectively.

Southern Grey-headed Sparrow

During phase 1 Southern Grey-headed Sparrows responded to time of day as an independent variable with a drinking peak event at late afternoon. However, during phase 2 time of day interacted significantly with increases in air temperatures where bird numbers kept rising consistently throughout the day especially at late afternoon (estimate = 0.07, $z = 10.03$, $p < 0.001$). There was a significant increase in the use of shaded waterholes by Southern Grey-headed Sparrows when compared to unshaded waterholes after shades were put up at phase 2 (estimate = -0.38, $z = -3.55$, $p < 0.001$; Figure 11).

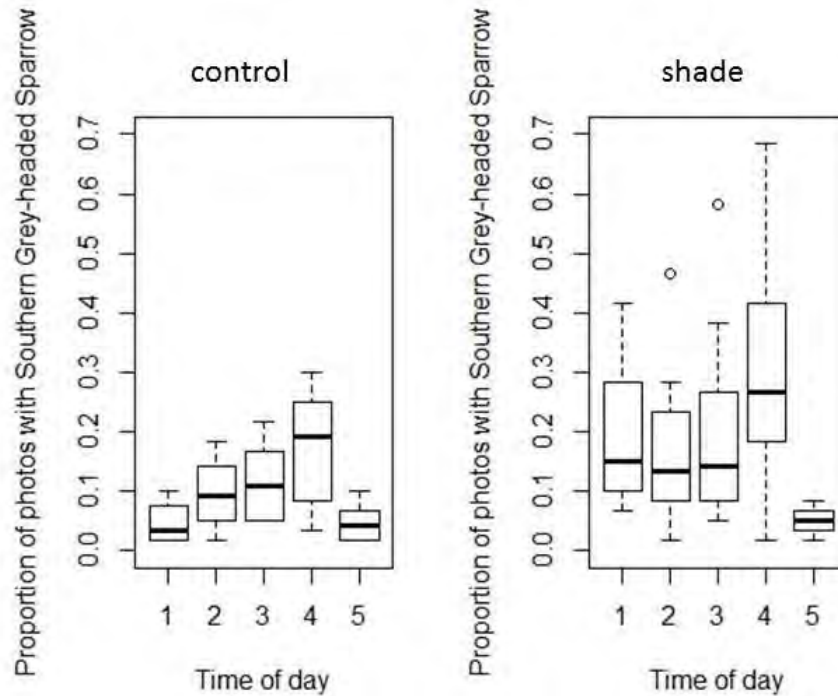


Figure 11: The proportion of photos with Southern Grey-headed Sparrow at different times of the day at control (unshaded) and shaded waterholes (1=6-7h00, 2=9-10h00, 3=12-13h00, 4= 15-16h00 and 5= 18-19h00).

Laughing Dove

The interaction between time of day and temperature was strong although negative with bird numbers dropping as temperatures rose early in the morning and at midday but increasing with increasing air temperature at late morning, late afternoon and evening at control and shaded waterholes during experimental phase 2 (estimate = -0.03, $z = -4.52$, $p < 0.001$). This was similar to the drinking pattern in phase 1 except during the late morning (9–10h00) when Laughing Doves decreased in number. However, the proportion of photos with Laughing Doves was higher at the shaded waterholes when compared with the control particularly at noon (estimate = 0.28, $z = 4.31$, $p < 0.001$; Figure 12).

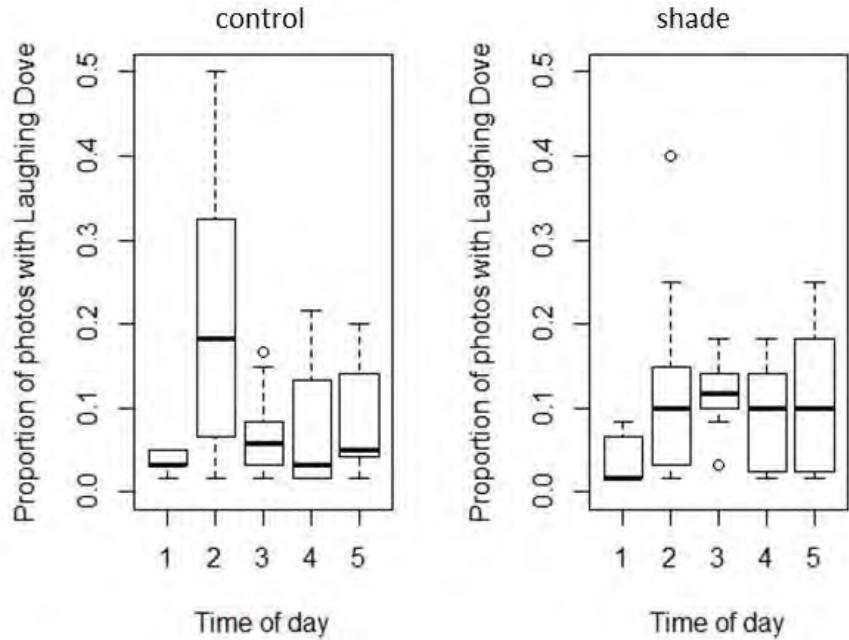


Figure 12: The proportion of photos with Laughing Doves at different times of the day at control (unshaded) and shaded waterholes (1=6-7h00, 2=9-10h00, 3=12-13h00, 4= 15-16h00 and 5= 18-19h00).

Black-throated Canary

There was a strong positive interaction between time of day and temperature (estimate = 0.03, $z = 0.01$, $p = 0.02$), and an extremely strong relationship between temperature and treatment (estimate = 0.17, $z = 3.92$, $p < 0.001$; Figure 13). As air temperatures increased, numbers drinking at unshaded waterholes decreased but increased at shaded waterholes. Occurrence (proportions of photos per hour) was higher at shaded than control waterholes at all times of day (estimate = -0.60, $z = -2.22$, $p = 0.03$; Figure 14). However, there was no significant interaction between variables during phase 1.

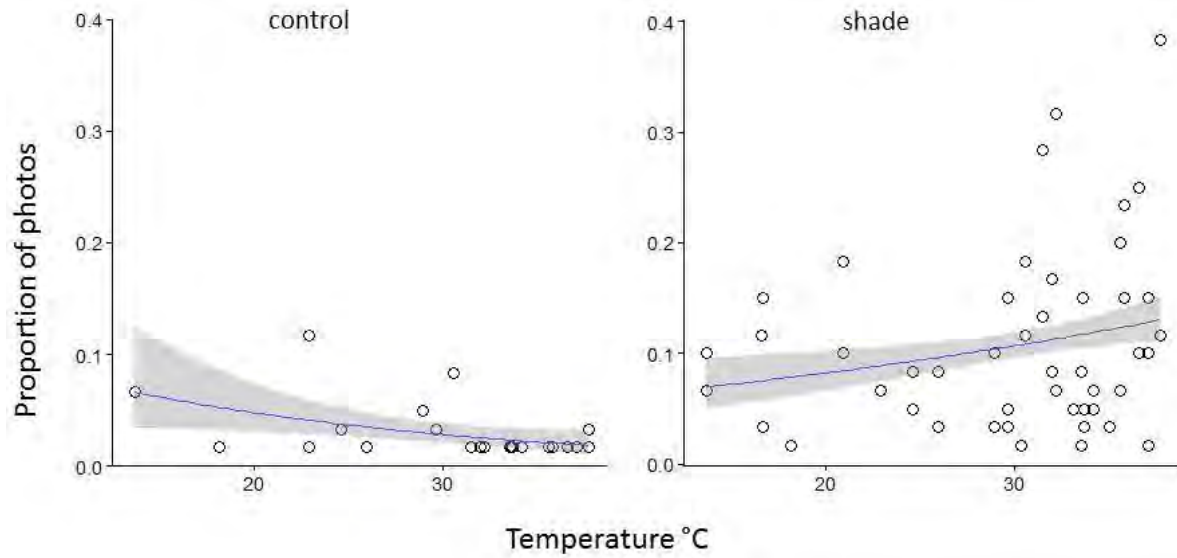


Figure 13: The proportion of photos with Black-throated Canary as a function of temperature at unshaded (control) and shaded waterholes respectively.

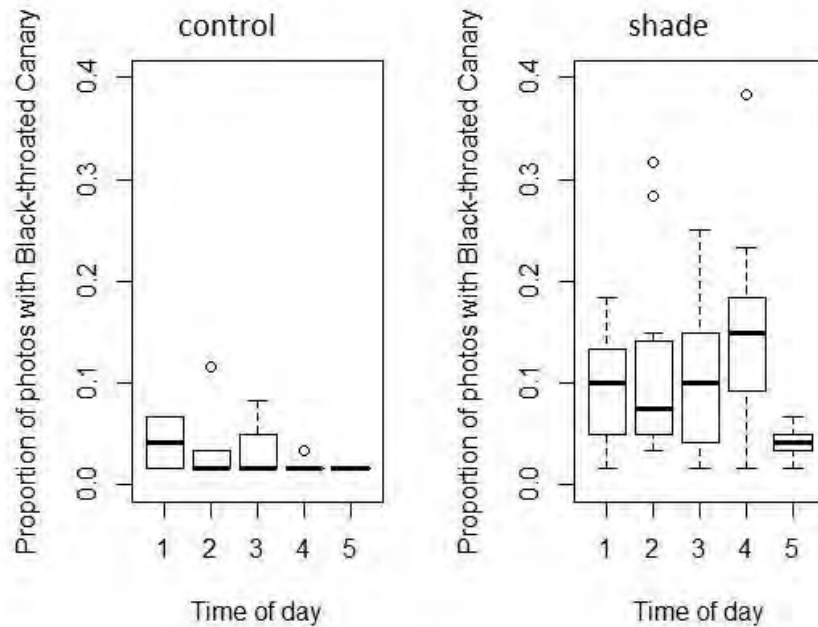


Figure 14: The proportion of photos with Black-throated Canary at different times of the day at control (unshaded) and shaded waterholes (1=6-7h00, 2=9-10h00, 3=12-13h00, 4= 15-16h00 and 5= 18-19h00).

Namaqua Dove

The only significant variable in the model ran for Namaqua doves was the time of day during this phase (estimate = 1.18, $z = 2.12$, $p = 0.03$). Although at phase 1 these birds responded to air temperatures and time of day independently. Similarly in phase 1 there was a positive effect with time of day on the proportion of photos with the highest number recorded in the morning and at noon.

Violet-eared Waxbill

The Violet-eared Waxbill just like the White-browed Sparrow-weavers only had temperature as an independent variable being significant. Although, temperature had a negative effect with bird numbers dropping (estimate = -0.03, $z = -2.45$, $p = 0.01$). Temperature had no significant effect on Violet-eared Waxbills in phase 1.

White-browed Sparrow-weaver

These birds showed no significant interactions between time of day, temperature or treatment. However, White-browed Sparrow-weavers increased frequency of visits to waterholes as air temperatures rose, regardless of whether the waterholes were shaded or not at the second phase of the experiment (estimate = 0.06, $z = 3.77$, $p < 0.001$). This is the same trend I observed during experimental phase 1.

Discussion

Overall, my study found that the addition of shade to waterholes had a significant effect on the drinking behaviour of six out of ten common Kalahari bird species analyzed. However, not all six species responded positively to the provision of shade. A concurrent study which took place at the same study area supports Smit's (2013) findings that half of the common bird species identified in this community utilized waterholes (Abdu n.d.). It is important to note that bird species never sighted drinking (such as the Chestnut-vented Tit-babbler) and those found drinking occasionally (such as the Scaly-feathered Finch and Black-chested Prinia) are very common within this community (pers. Obs.). From Smit's (2013) previous study most of the Kalahari birds dependent on free-standing surface water were identified as granivores. These birds are difficult to classify into dietary groups as only a few feed mainly on a particular diet. The Cape Turtle-Dove, Namaqua Dove, Laughing Dove and Violet-eared Waxbill are considered granivores because seeds comprise a major part of their diet (Hockey et al. 2005). The Sociable Weaver as well feeds primarily on insects while other species such as the White-browed Sparrow-weaver has a highly variable diet, feeding on insects, seeds, fruits as well as leaves (Hockey et al. 2005).

The majority of the 10 bird species analyzed are found all year round in the Kalahari except for highly nomadic species such as Wattled Starlings and Red-headed Finches, which may depart in response to the availability of food and water (Hockey et al. 2005). Few species such as Black-throated Canaries, Namaqua Doves and Violet-eared Waxbills also move locally within their ranges predominantly north-east South Africa (Hockey et al. 2005). The Cape Turtle-Dove and Sociable Weaver were resident species among others considered as 'abundant' in the Kalahari, each of which has seeds present in their diets (Maclean 1970). Amongst the nomadic species the

Namaqua Dove was one of the species described as ‘abundant’ (Maclean 1970). This relates to their current abundance around waterholes in this study. The movement of these birds could have an effect on the drinking patterns in relation to temperature dependency at different times of the year.

Water is the major driver of vegetation structure and persistence while species and structural diversity are highly dependent on the quality of desert ecosystems (Tews et al. 2004). Commuting to drink incurs travel costs and interrupts foraging activities, and thus impacts both energy expenditure and intake. In addition, bird community structures were altered decades ago when livestock were introduced (Perkins 1996) into the semi-desert Sandveld (land characterized by dry, sandy soils) known to be comprised of a variety of unaffected savannah tree species supporting high species diversity (Debenham 1952). Artificial waterholes are provided for livestock which are usually moved from one place to another occasionally (Perkins 1996). Waterholes are often fully exposed to the sun with little surrounding vegetation, so birds have to remain at some distance away to shelter from the sun (Tolsma et al. 1987) and predation. Overstocking of livestock and overgrazing have degraded rangelands causing a ‘piouspheric effect’ around waterholes (Perkins 1996). Restoration of these sites seems impossible (Stoddart et al 1975) because of the concentration of waste (dung and urine) released by livestock into the soil (Perkins 1996). However, these artificial waterholes could be advantageous to some bird species in compensating for water loss associated with elevated air temperatures and reduced foraging in spite of degradation around waterholes.

Responses of bird species

The reasons for avoiding waterholes at midday could be to avoid high environmental temperatures which come with costs of dehydration or hyperthermia and rather spend more time drinking at cooler temperatures of the day (Smit 2013). A number of factors played a role in the number of birds visiting waterholes. Sociable Weaver colonies bordering waterholes in my study may be contributing to the peak at some waterholes. Relatively low numbers at some of these waterholes may be as result of close distances (~200 m) to the road with disturbances coming from automobile engines and also from human structures such as abandoned buildings and houses located close by. The activity from livestock and other wild game animals at waterholes may also have an effect as large congregations prevent birds from drinking.

Warmer temperatures (29.4°C) and the moderate amount of rainfall (9.1 mm) observed in the second half of the experiment may have contributed to the decrease in the number of birds visiting waterholes. Dead grasses, leaves or remains from dead trees serve as a substratum for insects (Immelmann 1969). As temperatures continue to rise these insects may find their way to the top of the substratum especially at the start of the rains to cool off. The beginning of the rainy season is associated with a stream of insects (such as ants, termites, and caterpillars), millipedes, new fruits and water-rich seeds which provide birds with preformed water (Coaton 1963).

The trade-off between dehydration avoidance (via drinking at hot temperatures) and hyperthermia avoidance (via minimizing time spent drinking) in hot, sunlit microsites is displayed in Red-headed Finches, Black-throated Canaries, Cape Glossy Starlings and Laughing Doves at waterholes. Drinking under cooler (shaded waterholes) temperatures may be an advantage taken by these birds. For example, Cactus Wrens (*Campylorhynchus brunneicapillus*)

were observed to remain within shaded microsites while reducing visits to nests at air temperatures of about 35°C in the Sonoran Desert (Ricklefs and Hainsworth 1968). Irwin (1956) noted that Laughing Doves in Botswana had two drinking peaks (morning and late in the evening) while in the Namib Desert they had a main peak in the morning and a lesser one at midday (Willoughby and Cade 1967).

Other common species may have employed similar strategies in dealing with water costs at high temperatures but this was not picked up probably due to their higher distribution around unshaded waterholes. Some of these species could also have a slightly higher tolerance to heat stress. Namaqua Doves for example usually drink in the middle of the day when temperatures are high (Rowan 1983). They decreased their total daily water loss by 10% when compared with the Cloven-feathered Dove (*Drepanoptila holosericea*) even at air temperatures of over 40°C (Williams 1996; Schleucher et al 1991, Schleucher 1999). Diamond Doves (*Geopelia cuneate*) and Namaqua Doves (studied in captivity) may not go completely without water but they are able to reduce drinking events considerably and could sometimes go for two days without drinking (Schleucher 1993). In the Negev, Beersheba and Sinai Bedouin fowls (*Gallus domesticus*) when exposed to air temperatures of 45°C for 4 hours attained average body temperatures of 43.3°C and 43.6°C respectively (Marder et al. 1974). Similarly Violet-eared Waxbills could attain body temperatures of about 41.8°C (Anon 1976). In an attempt to remain hydrated White-browed Sparrow-weaver body temperatures have been observed to elevate by about 2.3°C during the warmest time of the day (Smit et al 2013). The Rock Pigeons (*Columba livia*) unlike the doves mentioned in this study as fledglings are able to withstand high air temperatures of about 50°C, as adults they develop a good respiratory mechanism and are able to withstand air temperatures that range between 48°C and 60°C (Marder and Gavrieli-Levin 1987).

Birds could be using shade for different purposes. In addition to this trade-off mentioned above, risks such as predation is associated particularly with avoiding hyperthermia due to the shade I provided at waterholes. Aside from aerial predators, ground predators such as mongooses and snakes put birds drinking at risk (Lazarus and Symonds 1992). To avoid heat stress associated with open grounds (Kenagy et al. 2004; Molokwu et al. 2010) or to hide away from predators (Molokwu et al. 2008) some animals are forced to forage closer to shaded microsites (Molokwu et al. 2010). However the presence of cover can be described as ‘protective’ and ‘obstructive’ to the prey or ‘obstructive’ to the predator. Molokwu et al. (2010) suggests that the risk of predation had a stronger influence on foraging bird behaviours than high temperatures within the African savannah (West Africa). Drinking in large groups is of advantage to Sociable Weavers where more eyes can watch out for predators (Ferns and Hinsley 1995). For example the Village Weavers (*Ploceus cucullatus*) and Speckle-fronted Weavers (*Sporopipes frontalis*) studied in the savannah foraged in the sun and only fled back to cover when pursued by a predator (Molokwu et al. 2010). The Red-headed Finches, Black-throated Canaries, Cape Glossy Starlings and Laughing Doves may be utilizing shade as cover in addition to taking advantage of cooler temperatures as demonstrated by the Rock Firefinch (*Lagonosticta sanguinodorsalis*) which preferred to remain within cover (shaded vegetation) away from predators (Molokwu et al. 2010). Cape Turtle-Doves, Laughing Doves and Namaqua doves arrived at waterholes individually or sometimes in pairs, usually perching on the wooden frames or tall trees scanning around before coming down to drink. Although no kills were recorded when the Southern Pale Chanting Goshawks or Gabar Goshawks came to drink, no other birds were seen at the waterholes or around it while they were drinking (pers. obs.). Falcons and goshawks were frequently observed hunting at artificial water points, mainly targeting doves in the Namib

Desert (Cade 1965). Cape Turtle-Doves and Namaqua Doves drinking at open waterholes may have associated shade with increasing predation risks (by reducing the visibility of predators). This was a similar observation made in Black-bellied Sandgrouse (*Pterocles orientalis*) which considered cover as being obstructive (Ferns and Hinsley 1995). Body mass could also contribute to a higher risk of predation. Cape Turtle-Doves, Cape Glossy Starlings and Laughing Doves could be more susceptible to predation because of their body masses relative to other birds species (Table 2) sighted drinking. Adult Cape Turtle-Doves weigh up to 148 g (Underhill et al. 1999) and tend to be abundant at waterholes as such they could be a good target for raptors such as the Southern Pale Chanting Goshawk.

Body size in birds is expected to have an impact on the trade-off between hydration and avoidance of hyperthermia. Smaller species such as Violet-eared Waxbills, Black-throated Canaries and Red-headed Finches are more likely to experience differences in environmental temperatures between shaded and unshaded microsites because the surface to volume ratio in birds increases with decreasing body size. Thereby, they lose water more quickly when heat stressed. In Verdins (*Auriparus flaviceps*) for example heat stress is lessened by about 12°C when resting within shaded microsites (Wolf and Walsberg 1996). In the Arabian Desert, Larks (Alaudidae) use thermally buffered burrows (41°C) of Egyptian spiny-tailed lizard (*Uromastyx aegyptia*) when air temperatures were about 44°C (William et al. 1999). In this study however, there was no clear pattern of this effect on the trade-off among the 10 bird species in relation to body size. For the smaller species, the Violet-eared Waxbill and Red-headed Finch are of the same size measuring 14 cm, while the Black-throated Canary is slightly smaller measuring 11 – 12 cm (Hockey et al. 2005). Although the Violet-eared Waxbill was observed to increase visits to waterholes, this was negligible in comparison to the Black-throated Canary and Red-headed

Finch numbers. In addition the increase in Violet-eared Waxbill could not be correlated with changes in air temperatures as noted in the other two species.

Finally, the availability of shade modifies the behavior of birds drinking at waterholes in the Kalahari. The Black-throated Canary and Red-headed Finch display a clear pattern that could be attributed to heat stress while shade could be utilized as cover from predators, species such as the Cape Turtle-Dove may rather resort to flying away from predators.

Conservation implications

In the face of increasing average and maximum air temperatures, birds such as Laughing Doves, Red-headed Finches, Cape Glossy Starlings and Black-throated Canaries can be partially managed by simply providing shade at drinking pools. This will aid in minimizing other challenges they face such as interruptions in breeding. However, if these bird species did not feel comfortable around artificial structures, waterholes could be moved within close distances to large *Acacia* and *Boscia* trees (common indigenous species) providing natural shade where birds can quickly fly to shelter during the heat or in avoiding predators. Less perceived predation risks at shaded waterholes may encourage non-drinkers to utilize it as cover. However, shade may be used by predators as well thereby increasing perceived predation risk as observed in the Cape Turtle-Dove. In addition, rotating access to certain waterholes frequently could potentially lead to the growth of vegetation around waterholes which could encourage more bird species to visit. Artificial waterholes though advantageous may have caused bird species to expand their geographical ranges as observed with the Crested Pigeon (*Ocyphaps lophotes*) and Zebra Finch (*Taeniopygia guttata*) in Australia (James et al. 1999).

Limitations of the study

During the course of study some of the limitations which could not be avoided or could be improved upon are as follows. Firstly, air temperatures during this study were not hot enough and hardly exceeded avian diurnal body temperatures (40-41°C) (Dawson and Schmidt-Nielsen 1964; Dawson and Bennett 1973). The trade-off between avoiding hyperthermia and dehydration may not be clearly defined by the birds in this region. Therefore carrying out a similar study in hotter regions (maximum air temperatures of about 45°C and above) such as Australia and North America (Wolf 2000) may provide a firmer conclusion. Secondly, the time frame allocated may have not been sufficient enough to view other changes exhibited by some bird species in responding to the presence of shade and needed more time to acclimatise. A longer time frame could also provide a larger sample size which is of importance in statistical analysis. Thirdly, the Kalahari rains arriving in October and November made temperatures on some days cooler for these birds and therefore had no reason to visit waterholes. Fourthly, the effect of the surrounding vegetation and animals drinking on bird visitations was not analyzed. Lastly, the shade cloth (dark blue in colour) and design may have prevented some bird species from drinking at waterholes because they looked foreign. Inventing new shade designs with more natural materials and taking into account the location and orientation of waterholes may improve the pattern of utilization by birds.

Conclusions and recommendations

Provision of shade increased the numbers of Laughing Doves, Black-throated Canaries, Red-headed Finches and Cape Glossy Starlings drinking at waterholes. This potentially enhanced their ability to remain hydrated and maintain a stable body temperature in response to potentially

increasing environmental temperatures. However, not all species benefited from the provision of shade, with numbers of Cape Turtle-Doves and Namaqua Doves decreasing when waterholes were shaded. Factors that might explain this include nervousness of the novel structures, or increased fear of predation due to impaired lines of sight. As a complement to this study, other aspects which could improve the knowledge about these birds and how they react to environmental changes include: 1) studying the duration of time spent drinking by different bird species at control waterholes versus shaded ones; 2) the amount of water swallowed on a single trip to waterholes (in relation to air temperature); 3) measuring vigilance of drinking birds at different times of the day; and 4) examining trade-offs between dehydration avoidance and predation avoidance by comparing the drinking pattern at a site with relatively fewer predators (such as Farm Murray) to one with higher number of predators (such as Kgalagadi Transfrontier Park). Together, answering these questions will improve our understanding of drinking behaviour in this environment.

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Appendices

Appendix A: Interactions between the experimental phase (exp; two levels ‘Before’ and ‘After’) and treatment group (treatment; two levels ‘Control’ and ‘Shade’) for the 10 selected species. Each species has its corresponding estimate, standard error, z value and p value respectively. Family = Poisson. (. = near significant, * = significant, ** = very significant and *** = extremely significant).

Species	Variables	Estimate	Standard Error	z value	P-value
Sociable weaver	(Intercept)	-1.2166	0.2783	-4.371	1.24e-05 ***
	treatmentshade	-0.8829	0.396	-2.229	0.0258 *
	expBefore	-0.1842	0.1907	-0.966	0.334
	treatmentshade:expBefore	0.4369	0.2697	1.62	0.1053
Cape-turtle dove	(Intercept)	-1.45802	0.14825	-9.835	< 2e-16 ***
	treatmentshade	-1.13144	0.21519	-5.258	1.46e-07 ***
	expBefore	-0.23743	0.04928	-4.818	1.45e-06 ***
	treatmentshade:expBefore	1.01724	0.08419	12.083	< 2e-16 ***
Cape glossy starling	(Intercept)	-2.65528	0.31543	-8.418	< 2e-16 ***
	treatmentshade	0.54523	0.4431	1.231	0.219
	expBefore	0.81829	0.07117	11.498	< 2e-16 ***
	treatmentshade:expBefore	-0.35622	0.09141	-3.897	9.75e-05 ***
Red-headed finch	(Intercept)	-2.10627	0.25863	-8.144	3.82e-16 ***
	treatmentshade	-0.17235	0.36638	-0.47	0.6381
	expBefore	0.12645	0.06035	2.095	0.0361 *
	treatmentshade:expBefore	-0.58616	0.09585	-6.116	9.62e-10 ***
Southern grey-headed sparrow	(Intercept)	-2.5191	0.2218	-11.36	< 2e-16 ***
	treatmentshade	1.0505	0.2938	3.576	0.000349 ***
	expBefore	-0.3075	0.0892	-3.448	0.000565 ***
	treatmentshade:expBefore	0.1569	0.1021	1.537	0.124318
Laughing dove	(Intercept)	-2.37977	0.28352	-8.394	<2e-16 ***
	treatmentshade	-0.05117	0.40359	-0.127	0.8991
	expBefore	-0.03725	0.07071	-0.527	0.5983

Black-throated canary	treatmentshade:expBefore	-0.19266	0.1113	-1.731	0.0835 .
	(Intercept)	-3.7309	0.3598	-10.369	<2e-16 ***
	treatmentshade	1.2297	0.4839	2.541	0.0110 *
Namaqua dove	expBefore	0.1219	0.2323	0.525	0.5997
	treatmentshade:expBefore	-0.4316	0.2479	-1.741	0.0816 .
	(Intercept)	-2.85263	0.09896	-28.826	<2e-16 ***
Violet-eared waxbill	treatmentshade	-0.2939	0.17884	-1.643	0.1003
	expBefore	-0.28286	0.13349	-2.119	0.0341 *
	treatmentshade:expBefore	0.37266	0.22013	1.693	0.0905 .
White-browed sparrow-weaver	(Intercept)	-3.20853	0.30121	-10.652	<2e-16 ***
	treatmentshade	-0.07962	0.39423	-0.202	0.84
	expBefore	-0.01898	0.15568	-0.122	0.903
	treatmentshade:expBefore	-0.18878	0.24791	-0.761	0.446
	(Intercept)	-2.8981	0.2109	-13.739	< 2e-16 ***
	treatmentshade	-0.2122	0.2973	-0.714	0.475336
	expBefore	-0.8137	0.2169	-3.752	0.000175 ***
	treatmentshade:expBefore	0.3243	0.2683	1.209	0.226751

***= extremely significant ($p < 0.001$), **= very significant ($0.01 > p > 0.001$), *= significant ($0.1 > p > 0.01$) and .=near significant ($p < 0.1$)

Appendix B: Models for the 10 selected bird species during Phase 1 of the experiment. The variables include: time of day, quadratic function of time of day, air temperature, waterhole and the interaction between time of day and air temperature. Each species has its corresponding Degree of freedom (df), Loglikelihood (LogLik), Akaike Information Criterion (AICc) and Weight (Wt).

Species	Models						df	logLik	AICc	delta	weight
	(Int)	h.2	h.2 ²	T _a	wtr	h.2:T _a					
Sociable Weaver	-0.453	0.3498	-0.3152	-0.06866	+	0.04355	10	-1108.32	2237.7	0	1
Cape Turtle-Dove	-1.102	-2.281	0.5118	0.1759	+	-0.04112	10	-879.14	1779.3	0	1
Cape Glossy Starling	-1.138	-0.03905	-0.1457	-0.01301	+	0.01802	10	-766.689	1554.6	0	0.999
Red-headed Finch	-3.409	0.6638	-0.09444	0.04089	+	-0.01583	10	-581.205	1183.6	0	0.79
Southern Grey-headed Sparrow	-0.7371	-0.7226		0.01626	+	0.008135	9	-714.973	1449	0	0.583
Laughing Dove	-4.369	0.3444		0.08369	+	-0.0221	9	-516.275	1051.6	0	0.702
	-4.357	0.2262	0.02609	0.09293	+	-0.0243	10	-516.011	1053.3	1.72	0.298
Black-throated Canary	-2.998		-0.06006	0.04819	+		8	-168.604	355.4	0	0.383
	-3.305	0.4496	-0.1273	0.0365	+		9	-167.766	356.3	0.92	0.242
	-3.564	0.1128		0.08682	+	-0.01627	9	-167.912	356.6	1.21	0.209
Namaqua Dove	-4.484	0.2339		0.07228		-0.01559	4	-177.548	363.5	0	0.167
	-3.643		-0.03601	0.03072			3	-178.65	363.6	0.03	0.165
	-3.404	-0.2272		0.03359			3	-178.833	363.9	0.4	0.137
	-4.12		-0.03929	0.03608	+		8	-173.421	364.5	0.94	0.105
	-3.85	-0.2504		0.03937	+		8	-173.526	364.7	1.15	0.094
	-4.442	0.02525	0.0546	0.08846		-0.0203	5	-177.378	365.4	1.88	0.065
	-4.729	0.1246		0.07088	+	-0.01271	9	-172.689	365.4	1.9	0.065
Violet-eared Waxbill	-3.506		-0.03209		+		7	-130.036	276.1	0	0.29
	-3.342	-0.1682			+		7	-130.51	277	0.95	0.181
	-3.604	-0.3099		0.02381	+		8	-129.277	277.2	1.1	0.167
	-3.772		-0.04609	0.01458	+		8	-129.378	277.4	1.3	0.151
White-browed Sparrow-weaver	-4.649			0.04078			2	-85.625	175.5	0	0.276
	-3.421	-0.7475		0.00304		0.02257	4	-83.418	175.6	0.11	0.261
	-4.68	-0.08312		0.05129			3	-85.317	177.1	1.61	0.124
	-3.344	-0.3228	-0.1047	-0.03955		0.0331	5	-83.043	177.2	1.75	0.115
	-4.722		-0.00936	0.04738			3	-85.429	177.3	1.83	0.111

Appendix C: The pattern of use of waterholes by the 10 selected species during phase 1 of the experiment. The variables include: intercept (waterhole 1) waterhole (2, 3, 4, 6 and 8), air temperature, time of day, quadratic function of time of day, interaction between air temperature and time of day. Each species has its corresponding estimate, standard error, t value and p value respectively. Family = Quasibinomial. (T_a = air temperature, h.2 = time of day, $I(h.2^2)$ = quadratic function of time of day, : = interaction, . = near significant, * = significant, ** = very significant, *** = extremely significant).

Sociable Weaver	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-0.45298	0.38162	-1.187	0.23664
waterholeWH2	-1.72817	0.24356	-7.095	2.22e-11 ***
waterholeWH3	-1.2867	0.21067	-6.108	5.22e-09 ***
waterholeWH4	-0.59408	0.18589	-3.196	0.00162 **
waterholeWH6	0.21273	0.16243	1.31	0.19181
waterholeWH8	-0.95003	0.20853	-4.556	9.09e-06 ***
T_a	-0.06866	0.03074	-2.233	0.02666 *
h.2	0.34982	0.33471	1.045	0.29722
$I(h.2^2)$	-0.31521	0.07442	-4.236	3.48e-05 ***
$T_a:h.2$	0.04355	0.01017	4.284	2.86e-05 ***

Cape Turtle-Dove	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-1.10208	0.305204	-3.611	0.000375 ***
waterholeWH2	-1.02926	0.179438	-5.736	3.08e-08 ***
waterholeWH3	-0.97673	0.175509	-5.565	7.35e-08 ***
waterholeWH4	-0.51544	0.151524	-3.402	0.000791 ***
waterholeWH6	-0.61094	0.155493	-3.929	0.000113 ***
waterholeWH8	-0.21724	0.144064	-1.508	0.132956
T_a	0.175885	0.023729	7.412	2.44e-12 ***
h.2	-2.28144	0.287078	-7.947	8.87e-14 ***
$I(h.2^2)$	0.511837	0.052467	9.755	< 2e-16 ***
$T_a:h.2$	-0.04112	0.006285	-6.542	3.98e-10 ***

Cape Glossy Starling	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-1.13756	0.343456	-3.312	0.001120 **
waterholeWH2	-0.51598	0.185061	-2.788	0.005874 **
waterholeWH3	0.046126	0.165506	0.279	0.7808
waterholeWH4	0.548548	0.156593	3.503	0.000581 ***
waterholeWH6	-1.62895	0.587071	-2.775	0.006112 **
waterholeWH8	-0.56443	0.187064	-3.017	0.002922 **
T _a	-0.01301	0.026887	-0.484	0.629065
h.2	-0.03905	0.320095	-0.122	0.903032
I(h.2 ²)	-0.1457	0.068848	-2.116	0.035713 *
T _a :h.2	0.018022	0.009089	1.983	0.048904 *

Red-headed Finch	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-3.4234	0.36253	-9.443	< 2e-16 ***
waterholeWH2	-0.24581	0.23533	-1.045	0.297594
waterholeWH3	-0.02596	0.21659	-0.12	0.904709
waterholeWH4	-0.46799	0.26077	-1.795	0.074332 .
waterholeWH6	1.22243	0.1775	6.887	8.52e-11 ***
waterholeWH8	0.98398	0.18277	5.384	2.18e-07 ***
T _a	0.0724	0.01532	4.726	4.50e-06 ***
h.2	0.32701	0.18743	1.745	0.082699 .
T _a :h.2	-0.0253	0.00639	-3.959	0.000107 ***

Southern Grey-headed Sparrow	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-0.7371	0.394623	-1.868	0.063515 .
waterholeWH2	-0.13832	0.182974	-0.756	0.450716
waterholeWH3	0.208163	0.171893	1.211	0.227586
waterholeWH4	-0.90681	0.22866	-3.966	0.000108 ***
waterholeWH6	-2.58476	1.024284	-2.523	0.012543 *
waterholeWH8	-0.79518	0.250422	-3.175	0.001779 **
T _a	0.016261	0.017657	0.921	0.358415
h.2	-0.7226	0.231689	-3.119	0.002135 **
T _a :h.2	0.008135	0.007505	1.084	0.279917

Laughing Dove	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-4.36862	0.595663	-7.334	8.87e-12 ***
waterholeWH2	0.69321	0.270431	2.563	0.011238 *
waterholeWH3	0.550974	0.285729	1.928	0.055493 .
waterholeWH4	1.262912	0.256543	4.923	2.02e-06 ***
waterholeWH6	0.427754	0.28312	1.511	0.132692
waterholeWH8	0.109294	0.302498	0.361	0.718323
T _a	0.083689	0.023736	3.526	0.000543 ***
h.2	0.344371	0.21845	1.576	0.116797
T _a :h.2	-0.0221	0.007892	-2.8	0.005697 **

Black-throated Canary	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-2.99811	0.32003	-9.368	9.69e-14 ***
waterholeWH2	-0.30947	0.1868	-1.657	0.102341
waterholeWH3	-2.0772	0.8301	-2.502	0.014823 *
waterholeWH4	-1.63878	1.01899	-1.608	0.112556
waterholeWH6	-0.94888	0.27174	-3.492	0.000861 ***
waterholeWH8	-1.81886	1.42622	-1.275	0.206674
T _a	0.04819	0.01323	3.642	0.000533 ***
I(h.2 ²)	-0.06006	0.01682	-3.57	0.000671 ***

Namaqua Dove	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-3.4037	0.29123	-11.687	<2e-16 ***
T _a	0.03359	0.01352	2.485	0.0147 *
h.2	-0.22719	0.09813	-2.315	0.0227 *

Violet-eared Waxbill	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-3.50648	0.38085	-9.207	7.1e-13 ***
waterholeWH2	0.19847	0.46849	0.424	0.67342
waterholeWH3	0.49706	0.54966	0.904	0.36964
waterholeWH4	-0.36643	0.88961	-0.412	0.68196
waterholeWH6	1.16407	0.3866	3.011	0.00388 **
waterholeWH8	0.65263	1.07521	0.607	0.54628
I(h.2 ²)	-0.03209	0.01571	-2.043	0.04568 *

White-browed Sparrow-weaver	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-4.64886	0.35273	-13.18	< 2e-16 ***
T _a	0.04078	0.0119	3.427	0.00114 **

Appendix D: Best models for the 10 selected bird species during Phase 2 of the experiment. The variables include time of day, quadratic function of time of day, air temperature, treatment ('control' and 'shade'), interaction between time of day and air temperature, interaction between time of day and treatment and interaction between air temperature and treatment. Each species has its corresponding Degree of freedom (df), Loglikelihood (LogLik), Akaike Information Criterion (AICc) and Weight (Wt).

Sociable weaver	Models	h.2	h.2 ²	T _a	trt	h.2:T _a	h.2:trt	T _a :trt	df	logLik	AICc	delta	Wt
	(Int)												
	2.343	-1.838	-0.2444	-0.1542	+	0.09765	+		7	-1089.163	2193.1	0	0.549
	2.416	-1.805	-0.2447	-0.1606	+	0.09795		+	7	-1090.084	2195	1.84	0.219

Cape-turtle dove	Models	h.2	h.2 ²	T _a	trt	h.2:T _a	h.2:trt	T _a :trt	df	logLik	AICc	delta	Wt
	(Int)												
	-2.612	-2.079	0.4903	0.1754	+	-0.03365	+		7	-605.85	1226.5	0	0.609
	-2.704	-2.099	0.4919	0.1805	+	-0.03378	+	+	8	-605.196	1227.4	0.93	0.382

Cape glossy starling	Models	h.2	h.2 ²	T _a	trt	h.2:T _a	h.2:trt	T _a :trt	df	logLik	AICc	delta	Wt
	(Int)												
	-1.929	-0.7942	-0.1372	-0.03316	+	0.04588			6	-465.221	943.1	0	0.312
	-2.088	-0.7386	-0.1382	-0.0335	+	0.04603	+		7	-464.154	943.2	0.08	0.299
	-2.209	-0.7811	-0.1396	-0.02503	+	0.04605		+	7	-464.342	943.5	0.46	0.248

Red-headed finch	Models												
	(Int)	h.2	h.2 ²	T _a	trt	h.2:T _a	h.2:trt	T _a :trt	df	logLik	AICc	delta	Wt
	-1.631	0.2325	-0.1676	-0.02401	+	0.01366		+	7	-590.862	1196.5	0	0.291
	-2.028		-0.06704	0.02107	+			+	5	-593.09	1196.6	0.07	0.282
	-2.108	0.2842	-0.1086	0.009839	+			+	6	-592.329	1197.3	0.72	0.203
	-1.588	0.261	-0.1669	-0.02842	+	0.0137	+	+	8	-590.589	1198.2	1.7	0.125

Southern grey-headed sparrow	Models												
	(Int)	h.2	h.2 ²	T _a	trt	h.2:T _a	h.2:trt	T _a :trt	df	logLik	AICc	delta	Wt
	-0.954	-1.295	-0.1863	-0.08834	+	0.07424	+	+	8	-470.308	957.8	0	0.579
	-1.358	-1.409	-0.1836	-0.064	+	0.07385	+		7	-471.782	958.5	0.67	0.415

Laughing dove	Models												
	(Int)	h.2	h.2 ²	T _a	trt	h.2:T _a	h.2:trt	T _a :trt	df	logLik	AICc	delta	Wt
	-4.047	-0.08611	0.09788	0.133	+	-0.03019	+		7	-442.488	900.1	0	0.524
	-3.96	-0.08049	0.09937	0.1295	+	-0.03036	+	+	8	-442.24	901.9	1.83	0.209

Black-throated canary	Models												
	(Int)	h.2	h.2 ²	T _a	trt	h.2:T _a	h.2:trt	T _a :trt	df	logLik	AICc	delta	Wt
	-0.4788	-0.6915		-0.1158	+	0.02625	+	+	7	-190.359	396.4	0	0.398
	-0.3485	-0.4	-0.09028	-0.1475	+	0.03536	+	+	8	-189.624	397.5	1.06	0.234

Namaqua dove	Models												
	(Int)	h.2	h.2 ²	T _a	trt	h.2:T _a	h.2:trt	T _a :trt	df	logLik	AICc	delta	Wt
	-4.255	1.183	-0.2308						3	-104.52	215.5	0	0.124
	-3.996	1.071	-0.2144		+				4	-103.383	215.6	0.08	0.12
	-3.711		-0.05928	0.04406	+				4	-103.64	216.1	0.59	0.093
	-4.216	1.158	-0.2168		+		+		5	-102.812	216.9	1.39	0.062
	-3.828		-0.05718	0.04383					3	-105.272	217	1.5	0.059
	-4.246	0.75	-0.1733	0.02547	+				5	-102.974	217.3	1.71	0.053
	-2.505		-0.03957		+				3	-105.41	217.3	1.78	0.051
	-4.468	0.9226	-0.1974	0.0208					4	-104.244	217.3	1.8	0.051
	-4.161		-0.05949	0.05846	+			+	5	-103.109	217.5	1.98	0.046

Violet-eared waxbill	Models												
	(Int)	h.2	h.2 ²	T _a	trt	h.2:T _a	h.2:trt	T _a :trt	df	logLik	AICc	delta	Wt
	-2.084			-0.02829	+				3	-113.288	233	0	0.113
	-1.642			-0.04628	+			+	4	-112.182	233.1	0.1	0.108
	-1.776		0.03216	-0.04674	+				4	-112.607	234	0.95	0.07
	-1.054	0.5685		-0.1149	+		+	+	6	-110.172	234	1	0.069
	-2.148			-0.03231					2	-114.925	234.1	1.04	0.067
	-1.881	0.1769		-0.05022	+				4	-112.721	234.2	1.18	0.063
	-1.412		0.02819	-0.06082	+			+	5	-111.664	234.5	1.48	0.054
	-1.484	0.1603		-0.06511	+			+	5	-111.718	234.6	1.58	0.051

White-browed sparrow-weaver	Models												
	(Int)	h.2	h.2 ²	T _a	trt	h.2:T _a	h.2:trt	T _a :trt	df	logLik	AICc	delta	Wt
	-4.835			0.05907					2	-137.08	278.3	0	0.142
	-2.641	-0.04115	-0.1452	-0.07614		0.03674			5	-134.099	279.2	0.82	0.094
	-3.166	-0.6736		-0.003836		0.02329			4	-135.368	279.4	1.03	0.085
	-4.681	0.07604		0.04626					3	-136.679	279.7	1.39	0.071
	-4.675		0.009197	0.05043					3	-136.761	279.9	1.55	0.065
	-4.803			0.05919	+				3	-136.954	280.3	1.94	0.054

Appendix E: The pattern of use of waterholes by the 10 selected species during phase 2 of the experiment. The variables include: intercept, air temperature, time of day, quadratic function of time of day, treatment ('control' and 'shade'), interaction between air temperature and time of day, interaction between time of day and treatment and interaction between air temperature and treatment. Each species has its corresponding estimate, standard error, t value and p value respectively. Family = Binomial. (T_a = air temperature, $h.2$ = time of day, $I(h.2^2)$ = quadratic function of time of day, : = interaction, . = near significant, * = significant, ** = very significant, *** = extremely significant).

Sociable weaver	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	2.34335	0.87438	2.68	0.00823 **
h.2	-1.83815	0.68151	-2.697	0.00783 **
$I(h.2^2)$	-0.24442	0.11318	-2.16	0.03247 *
T_a	-0.1542	0.05775	-2.67	0.00846 **
treatmentshade	-1.1711	0.43692	-2.68	0.00822 **
h.2: T_a	0.09765	0.02012	4.852	3.15e-06 ***
h.2:treatmentshade	0.11297	0.14204	0.795	0.42776

Cape-turtle dove	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-2.61218	0.301969	-8.65	< 2e-16 ***
h.2	-2.07866	0.201542	-10.314	< 2e-16 ***
$I(h.2^2)$	0.490315	0.038547	12.72	< 2e-16 ***
T_a	0.175365	0.021171	8.283	< 2e-16 ***
treatmentshade	-0.40138	0.169979	-2.361	0.0182 *
h.2: T_a	-0.03365	0.005021	-6.701	2.07e-11 ***
h.2:treatmentshade	-0.22194	0.045977	-4.827	1.39e-06 ***

Cape glossy starling	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-1.92897	0.406883	-4.741	2.13e-06 ***
h.2	-0.79418	0.278388	-2.853	0.00433 **
$I(h.2^2)$	-0.1372	0.04603	-2.981	0.00288 **
T_a	-0.03316	0.024679	-1.344	0.17904
treatmentshade	0.227567	0.075332	3.021	0.00252 **
h.2: T_a	0.045877	0.007949	5.772	7.86e-09 ***

Red-headed finch	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-1.63133	0.347163	-4.699	2.61e-06 ***
h.2	0.232529	0.23584	0.986	0.32415
I(h.2 ²)	-0.16759	0.049609	-3.378	0.00073 ***
T _a	-0.02401	0.023336	-1.029	0.30357
treatmentshade	-1.60326	0.29812	-5.378	7.54e-08 ***
h.2:T _a	0.013662	0.008013	1.705	0.08820 .
T _a :treatmentshade	0.047879	0.010057	4.761	1.93e-06 ***

Southern grey-headed sparrow	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-0.95401	0.432308	-2.207	0.027330 *
h.2	-1.29515	0.283258	-4.572	4.82e-06 ***
I(h.2 ²)	-0.18634	0.04338	-4.296	1.74e-05 ***
T _a	-0.08834	0.025662	-3.443	0.000576 ***
treatmentshade	0.938989	0.361683	2.596	0.009427 **
h.2:T _a	0.07424	0.007403	10.028	< 2e-16 ***
T _a :treatmentshade	0.031809	0.018455	1.724	0.084783 .
h.2:treatmentshade	-0.37889	0.106644	-3.553	0.000381 ***

Laughing dove	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-4.04736	0.437245	-9.257	< 2e-16 ***
h.2	-0.08611	0.265236	-0.325	0.7454
I(h.2 ²)	0.097881	0.047003	2.082	0.0373 *
T _a	0.132992	0.025381	5.24	1.61e-07 ***
treatmentshade	-0.87718	0.2196	-3.994	6.48e-05 ***
h.2:T _a	-0.03019	0.006678	-4.52	6.18e-06 ***
h.2:treatmentshade	0.279462	0.064884	4.307	1.65e-05 ***

Black-throated canary	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-0.47881	0.81962	-0.584	0.5591
h.2	-0.69152	0.45883	-1.507	0.13178
T _a	-0.11582	0.0415	-2.791	0.00526 **
treatmentshade	-1.91385	0.74536	-2.568	0.01024 *
h.2:T _a	0.02625	0.0108	2.431	0.01507 *
T _a :treatmentshade	0.16683	0.04253	3.923	8.76e-05 ***
h.2:treatmentshade	-0.6036	0.27219	-2.218	0.02658 *

Namaqua dove	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-4.2552	0.78751	-5.403	6.54e-08 ***
h.2	1.18273	0.55894	2.116	0.0343 *
I(h.2 ²)	-0.23077	0.09317	-2.477	0.0133 *

Violet eared waxbill	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-2.08418	0.31172	-6.686	2.29e-11 ***
T _a	-0.02829	0.01153	-2.454	0.0141 *
treatmentshade	-0.3027	0.16664	-1.817	0.0693 .

White-browed sparrow-weaver	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-4.83454	0.51246	-9.434	< 2e-16 ***
T _a	0.05907	0.01566	3.773	0.000161 ***