The impact of South Africa's largest photovoltaic solar energy facility on birds in the Northern Cape, South Africa

By Elke Visser

Minor Dissertation presented in partial fulfilment of the requirements for the degree of Masters of Science in Conservation Biology

Percy FitzPatrick Institute of African Ornithology, University of Cape Town, Rondebosch, 7701, South Africa

February 2016

Supervisors: P.G. Ryan, S. Ralston, and A.C. Cardenal

Plagiarism declaration

I know the meaning of plagiarism and declare that all of the work in the dissertation, save for that which is properly acknowledged, is my own.

Signature: Signed ………………………………

Date: 15 February 2016 ………………………………

Abstract

Renewable energy is a promising alternative to alleviating fossil fuel-based dependencies, but its development can require a complex set of environmental trade-offs for bird communities in the area, ranging from effective and physical habitat loss to direct collision-related mortality. The wide variation in the nature and significance of predicted impacts of utility-scale photovoltaic (PV) facilities on birds, and the low levels of confidence attending these predictions, has emphasised the need for scientific research. This study assesses the risks to bird populations and guilds at one of South Africa's largest PV developments. Firstly, in order to identify functional and structural changes in bird communities in and around the development footprint, bird transect data were gathered, representing the solar development, boundary, and untransformed landscape. Secondly, to assess the risk of collision mortality with solar-related infrastructure, representative samples (core vs. edge) were surveyed for bird carcasses and other signs of collision for three months covering 20-30% of the facility at search intervals of 4, 7 and 14 days. In order to account for potential biases in carcass detection, searcher efficiency and carcass persistence trials were conducted. The distribution of birds in the landscape changed, from a shrubland to open country and grassland bird community, in response to changes in the distribution and abundance of habitat resources such as food, water and nesting sites. These changes in resource availability patterns were detrimental to some bird species and beneficial to others. Shrubland specialists, such as the black-chested prinia (*Prinia flavicans*) and chestnut-vented tit-babbler (*Parisoma subcaeruleum*), appeared to be negatively affected by the presence of the PV facility. In contrast, open country/grassland and generalist species, especially species such as the Cape sparrow (*Passer melanurus*) and familiar chat (*Cercomela familiaris*), were favoured by its development. Utility-scale PV facilities inevitably will not substitute for the natural habitats they have replaced, but might offer opportunities for climate protection that do not necessarily conflict with nature conservation. Monitoring success of avian mortality was significantly influenced by variation in detection rates by size class (60 and 95% for birds <100 g and >100 g, respectively) and the location of carcasses relative to the solar panel units (65 and 90% for birds adjacent and under the units, respectively) as well as decreasing persistence rates per search interval (57, 53, and 40% after 4, 7, and 14 days, respectively). Only injuries associated with non-fatal collision of large-bodied birds with the underside of the panels and entrapment between fencing could be concluded with reasonable certainty. An extrapolated fatality estimate of 4.53 fatalities.$MW^{-1}.yr^{-1}$ (95% CI 1.51-8.50), short study period, and lack of comparable results from other sources made it difficult to provide a meaningful assessment on avian mortality at PV facilities. Despite these limitations, the few bird fatalities that were recorded might suggest that there is no significant link with collision-related mortality at the study site. In order to fully understand the risk of solar energy development on birds, further collation and analysis of data from solar energy facilities across spatial and temporal scales, based on scientifically rigorous research designs, is required.

Keywords: Renewable energy, utility-scale photovoltaic facilities, bird communities, habitat change, collision mortality

Table of Contents

Introduction

South Africa's role in solar energy development

According to the 2015 Climate Change Performance Index (CCPI), South Africa's heavy reliance on fossil fuels has ranked the country among the poorest performers in terms of their emissions level, development of emissions, and efficiency (Burck et al. 2015). Therefore, the country's energy planning system now requires that renewable energy play a significant role in the nation's power generation mix. According to the Copenhagen Agreement, South Africa pledged in December 2009 to take mitigation action towards the reduction of carbon emissions by 34 and 42% below the business-as-usual trajectory by 2020 and 2025, respectively (Eberhard et al. 2014); a goal that the renewable energy sector plays a major role in attaining. The National Electricity Regulations Act (ERA) of 2006 and the new generation capacity regulations have been the crucial legal instruments used by the government to unlock the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP). To date, three ministerial determinations have been issued for the procurement of 3 725 MW by 2016, 3 200 MW by 2020, and 6 300 MW by 2025 (DoE 2015). The allocated quantities are derived from the Integrated Resource Plan's (IRP) 2010-2030 target of 17 800 MW new generation capacity that has been set aside for renewables by 2030 (DoE 2015).

South Africa is well endowed with solar, biomass, and wind renewable energy sources where the geographic distribution of REIPPs broadly corresponds to the distribution of resource potential in the country. Most of South Africa is classified as semi-arid, with large expanses of flat terrain and high levels of irradiation, making it ideal for solar energy generation. South Africa has one of the highest potential solar energy regimes in the world with average daily direct normal radiation in excess of 7 KWh/m^2 (Eberhard et al. 2014). The Northern Cape, which has the most favourable radiation levels, has attracted the majority of the solar photovoltaic (PV) and all of the concentrated solar power (CSP) projects approved to date. The province hosts 48 of the 92 Independent Power Producers (IPP) projects in the country and is expected to contribute 3 566 MW to the total procured renewable energy capacity once construction is complete (DoE 2015).

Utility-scale solar developments are characterised by two basic types of technologies: photovoltaic and concentrated solar power. Photovoltaic systems convert solar radiation directly into electricity by exposing solar cells to incoming radiation. These cells are arranged conventionally in several flat panels, or include lenses or reflective surfaces to concentrate radiation onto a smaller group of more efficient cells (Hernandez et al. 2014). Concentrated solar power systems use arrays of reflective surfaces that are arranged as troughs, fresnels or dishes to focus the sun's heat onto a receiving element that contains a heat transfer fluid. The liquid is transferred to heat exchangers that produce steam in order to turn the turbines or generators that supply electricity (Hernandez et al. 2014). Out of the two technologies, PV has seen the most dramatic technological and cost advancements. Consequently, these facilities have contributed 2 292 MW in the five bid windows, which equates to more than a third of the total procured renewable energy capacity (DoE 2015). In terms of CSP, the total global capacity has remained relatively low mainly due to the comparatively high cost of the technology. However, CSP offers the added benefit of thermal storage with up to 12 hours supply capacity. Therefore, CSP technology has greater flexibility regarding the supply of electricity, making it a valuable contribution to the renewable energy portfolio (DoE 2015).

Solar energy development and birds

Despite the economic, social and environmental benefits of utility-scale solar facilities, its development can require a complex set of environmental trade-offs for bird populations and communities in the area. Direct impacts range from effective and physical habitat loss to collision or electrocution-related mortality, whereas the indirect impacts such as water depletion and dust deposition may extend beyond the development footprint (Lovich and Ennen 2011; Hernandez et al. 2014). However, the nature and magnitude of these impacts are generally related to the type of technology implemented. Each of the solar development systems have technological configurations that present markedly different hardware, and have widely differing spatial requirements per unit of power generated (Phillips 2013; Hernandez et al. 2014).

Impacts of PV developments

Utility-scale solar PV facilities tend to occupy large areas of approximately 2-5 ha per MW (Ong et al. 2013; Hernandez et al. 2014) and, in many cases, have involved the complete removal of vegetation from the inclusive footprint (Lovich & Ennen 2011; DeVault et al. 2014). It is this tendency to destroy, degrade, fragment or otherwise displace birds from large areas of their natural habitat that has stimulated most concern to date (Lovich & Ennen 2011), especially regarding species with restricted ranges and specific habitat requirements. In contrast, recent reports in Germany and the United Kingdom have provided empirical evidence indicating that utility-scale solar PV facilities enable the exploitation of synergies between climate protection and nature conservation. According to national studies conducted in 2005 to 2007 by the Federal Agency of Nature Conservation (BfN) and German Ministry of the Environment (BMU), brown sites such as landfills and previous agricultural fields were converted into biotopes of a higher value compared to its original state, e.g. Fürth-Atzenhof solar project (Peschel 2010; Parker & McQueen 2013), resulting in the attraction of novel species benefitting from the artificial provision of otherwise scarce resources such as perches, nest sites and shade (DeVault et al. 2014).

Recent findings at solar energy facilities in North America suggest that collision mortality impacts may be underestimated, especially at utility-scale PV facilities (Kagan et al. 2014). Hypotheses posit that collision trauma may be associated with polarised light pollution (PLP). Glare and polarised light emitted by the solar panels may attract insects to the development area as they perceive the panels as water bodies. This results in the aggregation of foraging birds, which could increase the risk of collision with solar-related infrastructure (Horváth et al. 2009, 2010; Lovich & Ennen 2011). The "lake-effect" hypothesis states that waterbirds themselves might mistake large expanses of solar arrays as water bodies, thereby colliding with the infrastructure as they attempt to land. This could either result in direct mortality or leave the individuals injured or stranded within the development area, rendering them unable to escape to safety or easily take-off from land when confronted by potential predators (Kagan et al. 2014). However, to date, there have been no studies to substantiate or refute either hypothesis (Lovich & Ennen 2011; Kagan et al. 2014; Waltson et al. 2015). The overall lack of evidence might be a reflection of the absence of monitoring effort rather than absence of collision risk.

Impacts of CSP developments

Similar to PV facilities, CSP developments include the use of large, reflective surfaces (heliostats or parabolic troughs) which can potentially introduce the risk of collision impact trauma by becoming ecological traps for insects and birds, especially aerial insectivores (McCrary et al. 1982). The extent thereof is comparable with high collision rates reported for large sections of exposed glass generally associated with high-rise buildings in the urban environment (Drewitt & Langston 2008). However, these reflective surfaces pose an additional source of avian mortality in the form of solar flux, which is concentrated in the airspace surrounding the receiver unit. To date, the power tower technology has stimulated most concern, exposing passing birds to the risk of being singed or incinerated as they aggregate close to the receiver that reaches temperatures exceeding 800°C (McCrary et al. 1982; Hernandez et al. 2014). Exposure to solar flux could either result in direct mortality or impairment of the individual's flight capability, with starvation or predation as a consequence (Kagan et al. 2014). Several monitoring programmes in the United States have reported high avian mortality rates comparable with, or in excess of, those estimated from some of the more impactful wind farms (Smallwood 2013; Kagan et al. 2014). A combination of these sources of injury or mortality is therefore considered to be one of the most obvious and potentially significant impacts of solar energy development on birds. Other known or perceived impacts of CSP facilities include the destruction or modification of extensive tracts of natural habitat, excessive use of water, and pollution resulting from the use of dust suppressants due to the lack of vegetation cover (Lovich and Ennen 2011; Hernandez et al. 2014).

Rationale behind this study

Utility-scale solar PV facilities are expanding rapidly in southern Africa, and while experiences in certain parts of the world suggest that the industry might be detrimental to bird populations and communities, the nature and implications of these effects remain poorly understood (Tsoutsos et al. 2005; Gunerhan et al. 2009; Lovich and Ennen 2011; Turney and Fthenakis 2011; Hernandez et al. 2014). Unlike some components generally associated with solar facilities (Bevanger 1994, 1998; Janss 2000; Anderson 2001; Gauthreaux & Belser 2006; Lehman et al. 2007; Drewitt & Langston 2008; Jenkins et al. 2010), there is presently no clear pattern in the types of birds negatively affected by the development as most peer-reviewed publications have only addressed the potential impacts that are yet to be proven by empirical evidence.

This study evaluated the risks to bird populations and guilds at one of South Africa's largest PV facilities by addressing the following: (1) the structural and functional changes in bird communities within and around the development footprint, (2) the extent of avian collision, and (3) how it compares to other PV facilities and energy sources, such as wind. Ultimately, the study attempts to improve the knowledge of the impacts of utility-scale PV facilities and assesses whether mitigation measures are warranted to ensure that the industry rolls out sustainably in South Africa.

Methodology

Study site

The study was conducted at the 96 MW Jasper PV solar facility (28°17′53″S, 23°21′56″E) which is located on the Humansrus Farm, approximately 4 km south-east of Groenwater and 30 km east of Postmasburg (Fig. 1). Construction at the site was completed in October 2014 and occupies the area alongside two other solar energy developments, namely the 75 MW Lesedi PV project, which has been operational since May 2014, and the 100 MW Redstone CSP power tower project, which will begin construction in 2016.

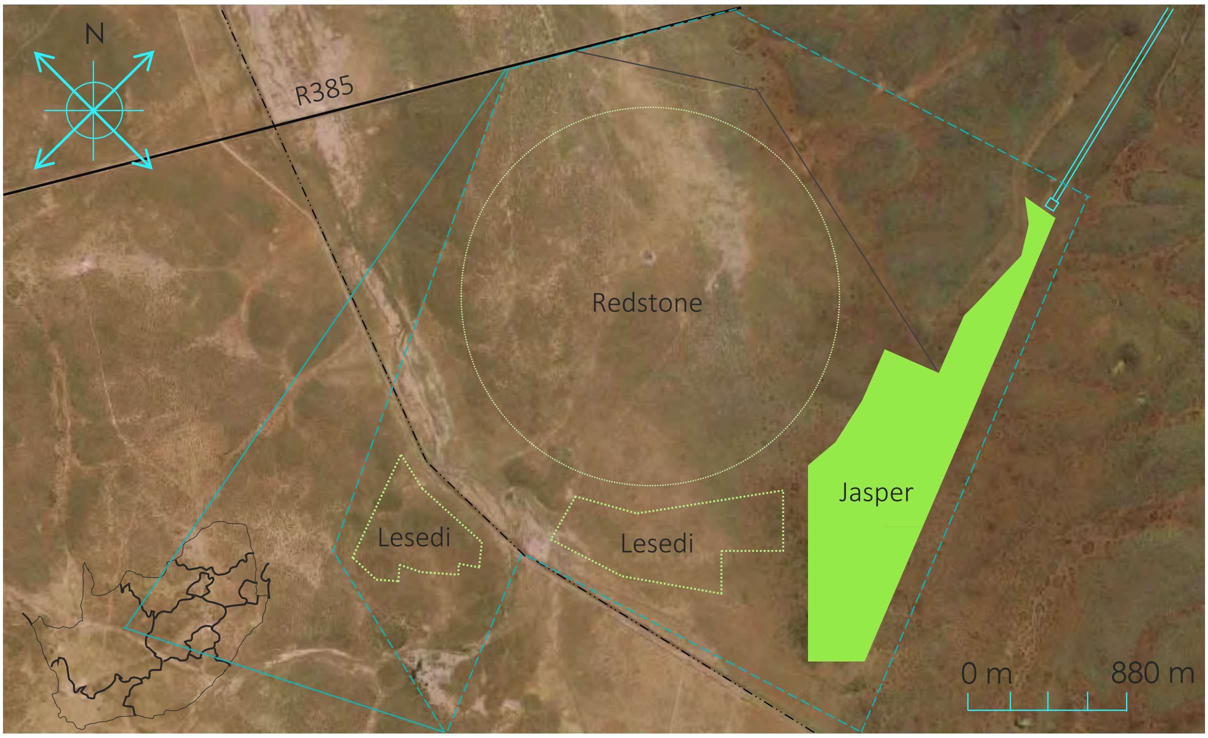


Figure 1: Layout of the three solar energy projects located between Postmasburg and Danielskuil in the Northern Cape, South Africa. This includes the 75 MW Lesedi and 96 MW Jasper solar photovoltaic facilities (operational) and the 100 MW Redstone concentrated solar power facility (planned). Map data©2015 AfriGIS (Pty) Ltd, Google.

About the Jasper PV facility

The Jasper PV facility contains 325 360 solar panels over a footprint of 180 hectares with the capacity to deliver 180 000 MWh of renewable electricity annually. The solar panel units (SPUs) face north at a fixed 20° angle, reaching a height of approximately 1.86 m relative to ground level with a distance of 3.11 m between successive rows of SPUs (Fig. 2a). Among the solar arrays, vegetation regrowth was promoted, where grass species such as *Eragrostis lehmanniana* and *Aristida congesta congesta* and forbs such as *Geigeria ornativa* and *Hermannia comosa* dominate the area. The facility, fence line, and roads remain largely free of any shrubs and woody vegetation through active removal and grazing practices. The facility is demarcated by a 7.28 km perimeter fence with a height of 3.35 m. The outer fence has a 100 × 50 mm ribbon mesh topped by three serrated ribbon strips, whereas the inner electric fence has horizontal slats of approximately 200 mm apart (Fig. 2b). Adjacent to the fence is a 20 × 20 m evaporation pond used to collect chemical-containing water from the panel cleaning process (Fig. 2c). A 50 to 150 m wide buffer zone, which remained untouched during the construction process, stretches around the facility and is demarcated by a fence separating the area from the Humansrus farm. The area north of the study site includes a 1 000 m^2 switchyard and 5 km transmission power lines (132kV) that join the Eskom Manganore-Silverstreams line onto the national grid. Bird flappers were installed on two transmission line sections of approximately 300 m, where visibility is impaired due to high background elevations.

Flora and avifauna

The study area lies within the Eastern Kalahari Bushveld bioregion of the Savanna Biome and consists of an open savannah grassland to dense bush with a well-developed tree layer, including species such as *Acacia luederitzii*, *Boscia albitrunca*, and *Rhus tenuinervis* (Mucina & Rutherford 2006; ERM 2011). The study area is characterised by one vegetation type, namely Olifantshoek Plains Thornveld. However, the higher rocky outcrops adjacent to the facility support Kuruman Mountain Bushveld where trees are less frequent, apart from *Searsia lancea* and *Olea europaea* subsp. *africana* (Mucina & Rutherford 2006; ERM 2011). The remainder of the farm is currently used for cattle and horse grazing. Based on the inspection of satellite imagery, there are no permanent or ephemeral rivers in the study area. However, there is a seasonal stream located south-west of the site, which is a tributary of the non-perennial Groenwaterspruit (ERM 2011). Several open water troughs are located at a communal area on the farm and could be used by various species, including large raptors, vultures, and smaller bird species such as the endemic and near-endemic sociable weaver (*Philetairus socius*), Cape sparrow (*Passer melanurus*), and red-headed finch (*Amadina erythrocephala*).

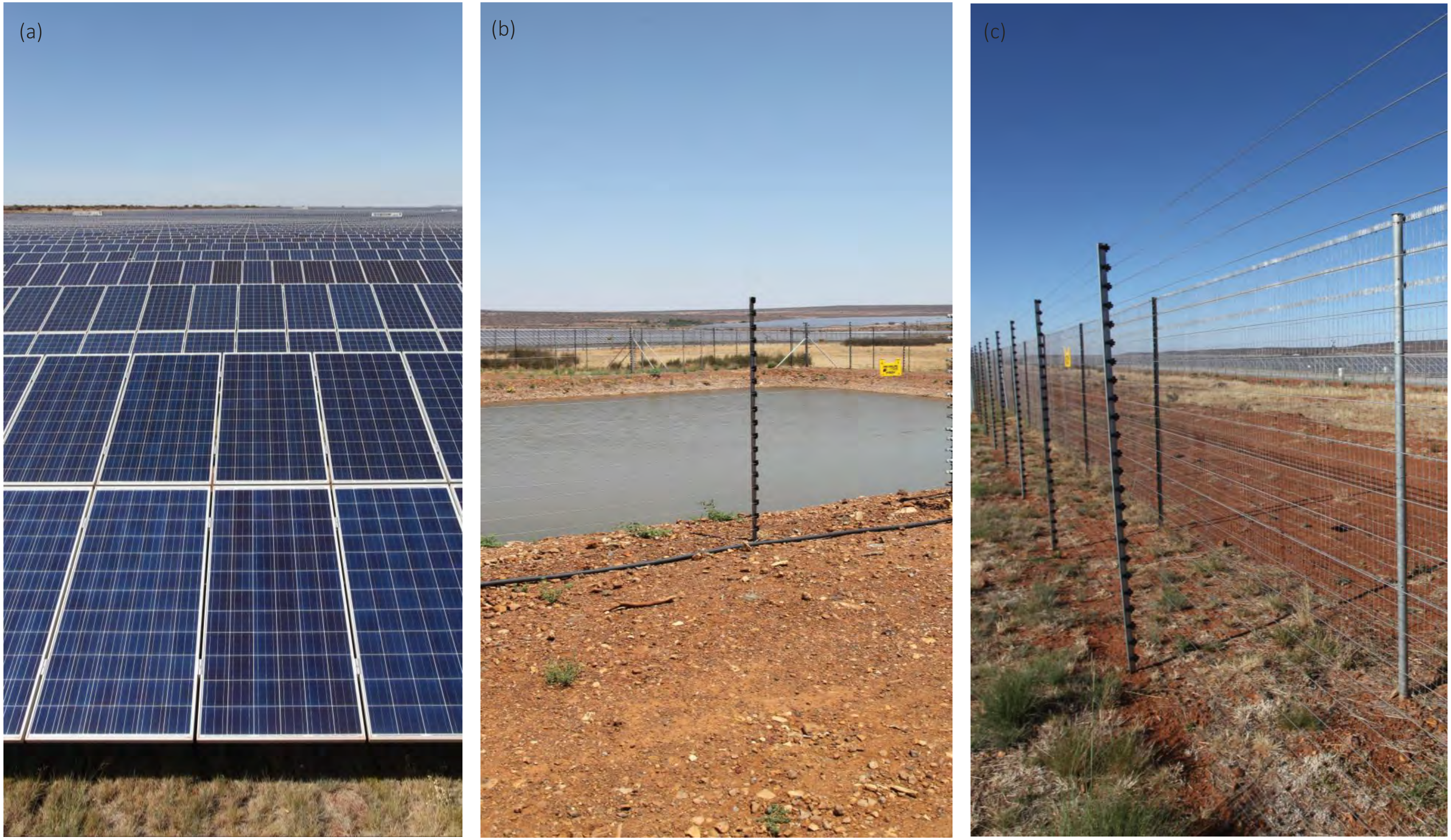


Figure 2: Visualisation of the solar-related infrastructure: (a) solar panels, (b) evaporation pond), and (c) perimeter fence at the Jasper PV solar facility in the Northern Cape, South Africa. Photos credited to P.G. Ryan.

The Savanna Biome is considered to have the most species-rich community in southern Africa and, although the study area does not overlap with any Important Bird Areas (IBAs), the habitat itself may be important for a suite of Red Data species. An estimate of 187 bird species could potentially occur within the study area, of which six are red-listed species and 53 are endemic/near-endemic to southern Africa (Appendix A; Taylor et al. 2015; SABAP2 2015). These include the white-backed (*Gyps africanus*) and lappet-faced vulture (*Torgos tracheliotos*), martial (*Polemaetus bellicosus*) and tawny eagle (*Aquila rapax*), and lanner falcon (*Falco biarmicus*) as well as the larger terrestrial secretarybird (*Sagittarius serpentarius*) and kori bustard (*Ardeotis kori*; ERM 2011). It also supports other raptor species such as the brown (*Circaetus pectoralis*) and black-chested snake eagle (*Circaetus pectoralis*), and the southern pale-chanting (*Melierax canorus*) and gabar goshawk (*Micronisus gabar*), and pygmy falcon (*Polihierax semitorquatus*). However, the scarcity of large trees means that large raptors and vultures are unlikely to breed in the study area. The habitat is also suitable for several non-Red Data endemic species such as the African red-eyed bulbul (*Pycnonotus nigricans*), ant-eating chat (*Myrmecocichla formicivora*), and northern black korhaan (*Afrotis afraoides*), and many near endemics namely the cape bunting (*Emberiza capensis*), yellow canary (*Crithagra flaviventris*), and Namaqua sandgrouse (*Pterocles namaqua*).

Changes in bird communities

Survey design

Bird community surveys were conducted from the 9th of November until the 6th of December 2015. The study site was classified into three habitat types: the solar facility, boundary (including the perimeter fence, evaporation pond, and buffer zone), and untransformed landscape (Fig. 3). Each survey was based on a regular sampling design with five 440-m transects per habitat type (2.2 km in total), ensuring at least 250 m between adjacent transects (Fig. 4). Each transect was surveyed for 40 minutes, with two 10-minute observations from elevated vantage points to allow for improved visibility, especially between the SPUs.

Control transects were selected based on information from the environmental impact assessment (EIA) to ensure that the physical conditions (slope, aspect, soil type, drainage) were similar to the solar facility and the habitat prior to construction (ERM 2011). Stratified sampling among major habitat types was not necessary due to the homogeneous nature of the terrain and vegetation type. The variation in habitat amounted to little more than subtle changes in the amount of ground cover and vegetation height. These types of physical differences were accounted for in order to reduce background variation, allowing any changes in bird communities to be more readily attributed to land management. The surveyed areas were monitored using identical methods to allow for comparable results.

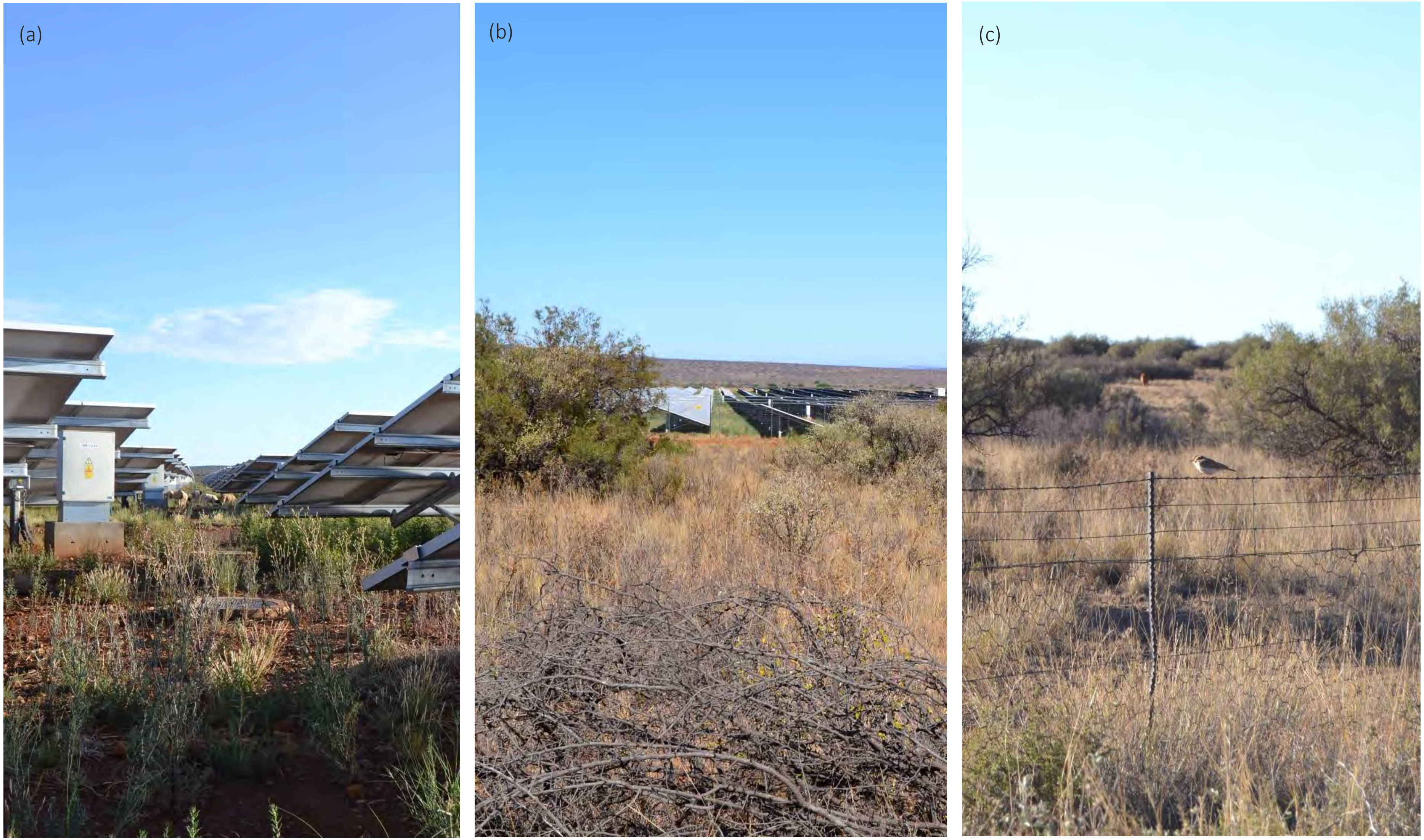


Figure 3: Visualisation of the three main habitat types: (a) The photovoltaic facility, (b) boundary (including the perimeter fence and the buffer zone), and (c) untransformed land adjacent to the buffer zone. Areas were surveyed to assess the changes in bird communities within and around the development footprint at the Jasper PV solar facility in the Northern Cape, South Africa.

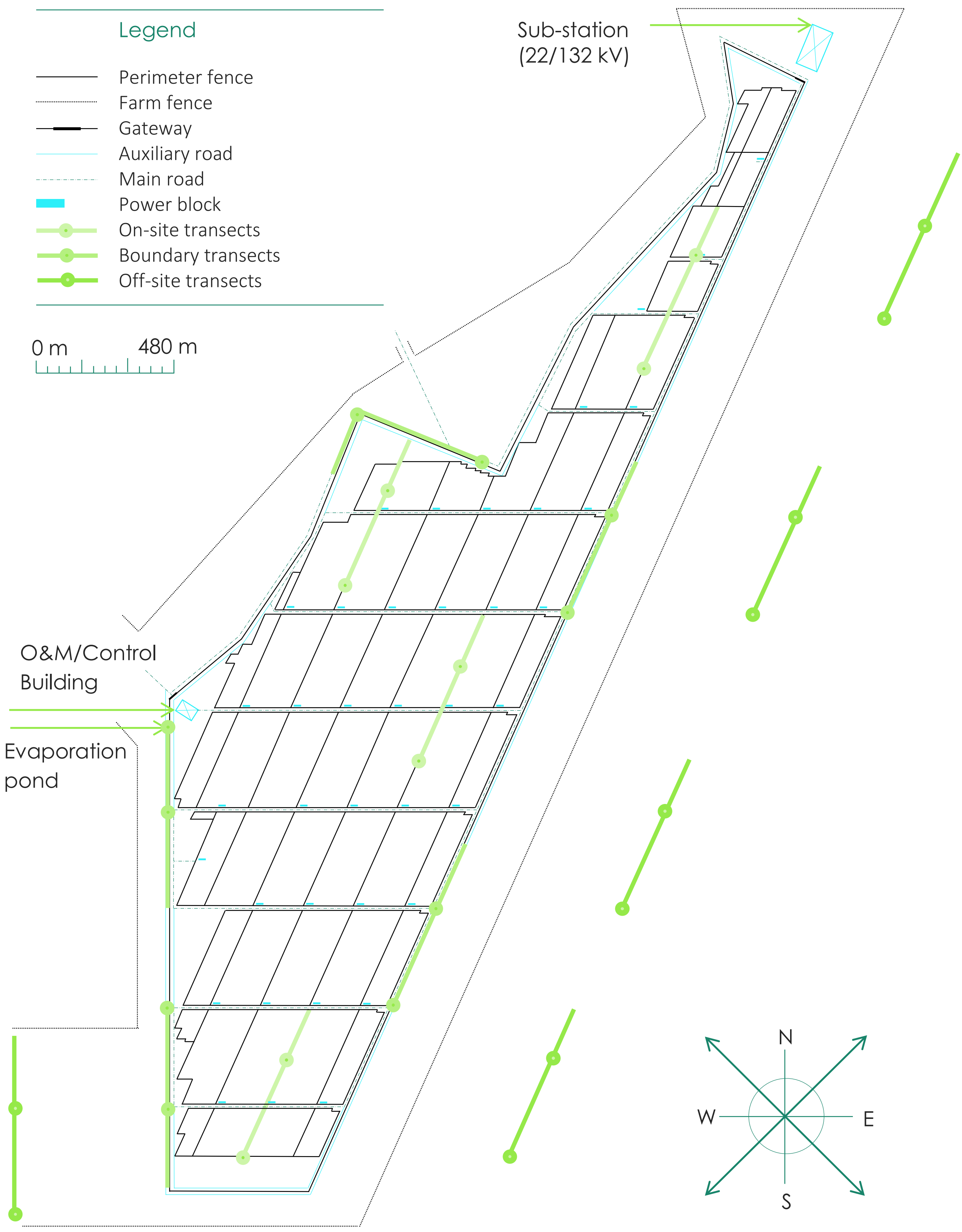


Figure 4: Sampling design to assess the changes in bird communities within and around the development footprint at the Jasper PV solar facility in the Northern Cape, South Africa. The linear transects, indicated in shades of green, represent the surveys conducted at the photovoltaic facility, boundary, and untransformed landscape.

Survey and data collection protocols

Transects were surveyed according to standard procedures and took into account possible biases caused by different observers, detectability, time of day, bird song activity and/or weather conditions (Bibby et al. 2000). All birds seen or heard were counted and identified with 8 x 40 Minolta binoculars, where the perpendicular distance between the transect line and observed bird was recorded. Surveys were conducted in the first four hours after sunrise when birds were most conspicuous and active, and were not conducted on days when weather conditions might affect bird activity, such as heavy rain, thunder storms, strong winds or thick mist (Bibby et al. 2000). The same surveyor was used to minimise observer bias and approximately two months, prior to the start of the surveys, was allocated to improve bird identification (Bibby et al. 2000). The sequence of observations was randomised among sites to ensure different starting points for each survey. This methodology was broadly consistent with those used in many other similar studies of small passerine densities in low shrubland (Bibby et al. 2000; Pearce-Higgins et al. 2006; Reinkensmeyer et al. 2008), and also generally compliant with the basic assumptions which must be met in order to analyse such data using Distance 6.0 software (Thomas et al. 2010). Additional observations were made regarding avian use at the PV facility, such as foraging and breeding.

Analysis

The Conventional Distance Sampling engine in Distance 6.2 release 1 was used to generate density estimates (birds.ha^{-1}) by search area (PV facility, boundary, and untransformed land) and most abundant species. Where relevant, evidence of heaping, responsive movement, outliers, and possible gross errors was investigated. Furthermore, suitable truncation points were determined and the grouping of exact distance data into appropriate intervals (0-20 m, 21-50 m, 51-100 m, 101-200 m, over 200 m) was performed (Buckland et al. 2001). Models were fitted to the data using all the available combinations of key functions and adjustment terms (uniform with cosine or simple polynomial, half-normal with cosine or Hermite polynomial and hazard-rate with cosine or simple polynomial) and assessed using the lowest Akaike's Information Criterion (AIC) values (Buckland et al. 2001). A Welch's t-test was used, through R 3.2.2 software, to assess the statistical difference of bird density (birds.ha^{-1}) between the three sample areas.

Correspondence Analysis (CA) was applied to the transect data to assess the variation in the distribution of bird species among the PV facility, boundary, and untransformed landscape by plotting the species and sample area scores on the first axis of the CA (e.g. Caplat & Fonderflick 2009). This allowed for further analysis in the magnitude of avoidance of certain species by selecting the 23 most abundant species within and around the development footprint, based on the density estimates. Each species *i* relative frequency within the development footprint γ_i (L_f) was compared to its frequency within the untransformed landscape γ_i (L_u) with the use of chi-square tests or Fisher exact tests (when one of the expected numbers was lower than 5) with a Bonferroni correction (e.g. Caplat & Fonderflick 2009). Species' individual frequency γ_i, was defined as the ratio of species *i*'s abundance on the total amount of individuals considered and plotted against each other. If species' scores are located at the straight line of equation $y = x$, species are indifferent. On the contrary, an effect of the solar development would split species above and under the identity line, placing overrepresented species amongst the facility above the line, and underrepresented species under the line. A low species frequency may account for two mechanisms: (1) A low density of the selected species, or (2) high densities of other species. Nevertheless, when compared to the reference frequency, it indicates how the local community differs from the regional species pool, which would be a measure of the relative effects of solar development on birds (e.g. Caplat & Fonderflick 2009).

Collision mortality

Survey design

Solar panel unit monitoring

Mortality surveys were conducted from the 14th of September 2015 until the 6th of December 2015, after the clearance surveys had been performed to remove any prior fatalities from the study area. Such fatalities occurred outside of known search intervals and, as a result, were not included in the fatality estimates. The study site was divided into three sample areas, each consisting of rows of SPUs arranged in solar arrays (Fig. 5). Each sample area was assigned ten arrays, which have been selected based on a spatial sampling design to ensure that the sample effort was distributed over the entire study area, representing the core, intermediate distance from the core, and edge (e.g. WEST 2015; Fig. 5).

Strickland et al. (2011) suggested that the search interval should ideally be shorter than the average carcass removal time. Therefore, the first set of solar arrays were searched every 4 days for the first six weeks and every 7 days thereafter, whereas the second set was surveyed every 14 days (Fig. 5). The area covered among the SPUs at the three sample areas amounted to 29920 panels (9%), 29920 panels (10%), and 29920 panels (9%), respectively, for the 4-and 7-day search interval and 24920 panels (8%), 32760 panels (10%), and 29560 panels (9%) for the 14-day search interval. This amounted to approximately 14 to 15 km of transects to be completed on the designated days. The coverage of each area, in terms of the aggregate solar energy hardware, ranged from 20 to 30% per search-interval category. The carcass searches consisted of surveying the area between every row of panels, where the area beneath the SPUs and the surfaces of the panels were checked for any signs of collision (feather sprays, blood spatter or dust imprints).

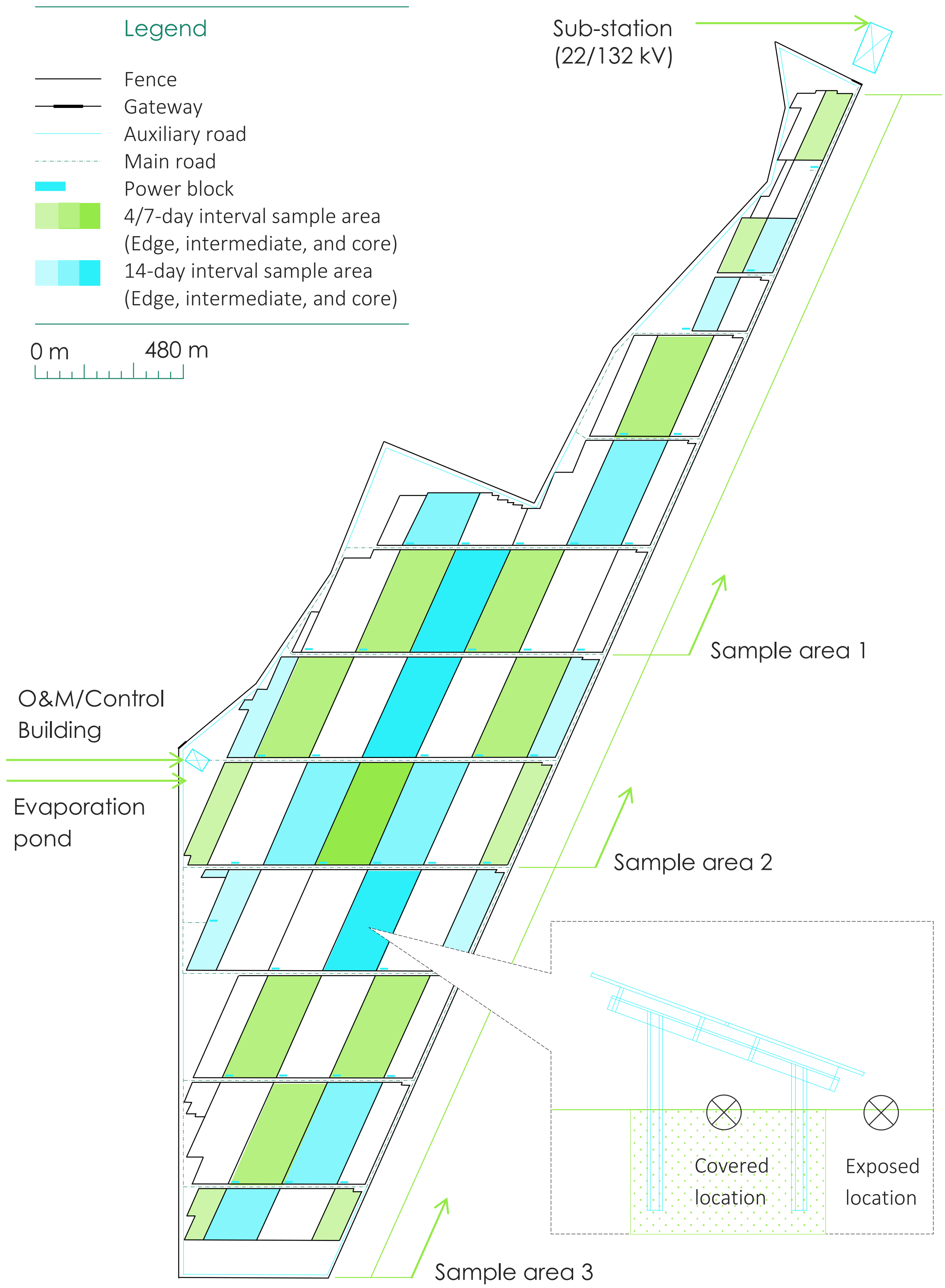


Figure 5: Sampling design to assess avian mortality at the Jasper PV solar facility in the Northern Cape, South Africa. The highlighted solar arrays indicate the samples, where the green and blue areas represent surveys conducted with a 4/7- and 14-day search interval, respectively. The enlarged PV panel schematic illustrates the placement of bird carcasses for the searcher efficiency and carcass persistence trials.

Substation and power line monitoring

In addition to monitoring the SPUs, the 1 000 m^2 substation was surveyed for bird carcasses or injured individuals. Surveys were conducted on foot, following the perimeter of the substation as access to the facility was restricted. The 5 km transmission power lines, which were erected to link the solar facility to the Eskom grid, were surveyed based on established protocols on the 21st of October, 12th of November, and 18th of November 2015. The surveys were conducted by two searchers on foot, following a meandering transect underneath the lines and surveying for fatalities within approximately 10-15 m of the transect line until the power lines merged with existing infrastructure (Anderson 2001; Shaw et al. 2010).

Perimeter fence and evaporation pond monitoring

The perimeter fence was segmented into and assigned to the three sample areas, with each section surveyed every 4, 7 and 14 days. The area covered at the perimeter fence amounted to 4.03 km (55%), 0.65 km (9%), and 2.60 km (36%) per sample area, respectively. Searches were conducted by vehicle, following the track alongside the inner fence. This proved to be suitable due to ease of navigation in close proximity to the fence line and the adequate level of visibility to detect fatalities. Travel speed did not exceed 10 km/h while conducting the surveys and the driver was always positioned closest to the perimeter fence to enhance visibility. In areas where the driving path diverged significantly from the fence, the survey was conducted by foot. The 20 × 20 m evaporation pond was checked every 4, 7 and 14 days, where each survey consisted out of walking adjacent to the fencing of the pond itself.

Survey and data collection protocols

Surveys were conducted before the heat of the day to limit fatigue due to heat exhaustion and, to ensure that data would be collected at different days and time frames, the sequence of surveys at the respective sample areas was randomised. All bird fatalities and injuries that were discovered during, or incidental to, the standard carcass surveys were recorded. Evidence of collision would be defined as: (i) smudge marks (e.g. blood or dust imprints) and feathers directly on solar hardware, (ii) feather spots consisting of at least two or more primary flight feathers, of at least five or more tail feathers, or two primaries within 5 m of each other, or a total of ten or more feathers of any type concentrated in an area less than 3 m^2, or (iii) whole or partial carcass with indications of predation, electrocution (e.g. burns) or collision (e.g. blunt force trauma). All data records included:

- Species classification based on identification, size class, taxonomic family, range (resident or diurnal/nocturnal migrant), and southern Africa Red list status
- Condition of remains: fresh (within a week old, with soft flesh remains and fresh feathers), recent (within two months old, with dried flesh remains and numerous feathers still present), fairly old (within a year old, with dry bones and possibly some old feathers remaining), or very old (older than one year, with bleached bones, no flesh or feathers)

- The suspected cause of fatality and level of certainty (Observed - 100%, valid - >90% certainty, probable - >50% certainty, possible - <50%, but > 0% certainty, not applicable - 0% certainty or unknown)
- Fatality location, which included the SPU number, the Global Positioning System (GPS) coordinates in Degrees Minutes (DM) with a Garmin nüvi, and where the fatality was found (e.g. underneath a SPU)
- Standardised description of the current habitat and visibility classes (Good, medium, or poor)
- Estimated weather conditions at time of mortality/injury

All physical evidence was photographed and either collected to avoid double-counting, bagged, carefully labelled, and frozen to await further examination, or marked on site if collection proved to be difficult. Handling of carcasses was limited, particularly when used in carcass persistence trials. Any carcasses found incidentally, was identified, photographed, and documented in the same manner as the regular surveys.

Searcher efficiency trials

The searcher efficiency trials were conducted on the 20th and 23rd of October 2015 to assess the probability of a carcass being detected among the SPUs (Morrison 2002; Barrios and Rodríguez 2004; Krijgsveld et al. 2009). Searcher efficiency rates can be estimated by several covariates such as season, habitat, and carcass size classes (Korner-Nievergelt et al. 2011; Strickland et al. 2011; Smallwood 2013). However, the trials of this study were managed in relation to SPU location (Adjacent or under the SPU) and size classes of birds (small, medium, and large) only. A total of 80 carcass detections per small (<100 g) size class, 40 for medium (100-1000 g), and 16 for large (>1000 g) was used during the trials (Appendix B). Placement at the perimeter fence, evaporation pond, substation, and power lines were not included in the study.

In order to account for potential biases, the placement of representative native or naturalised specimens for each trial did not exceed 24 hours in order to limit the number of trial carcasses placed on the landscape at any one time (Smallwood 2007). Another factor that influences carcass detectability is how fresh and intact the carcasses are (Smallwood 2007, 2013). However, in contrast to wind-energy projects, there is little expectation that the solar facility will cause injuries and fatalities that result in dismembered carcasses (Smallwood 2013). Therefore, the searcher efficiency trials conducted in this study only involved fresh intact carcasses. Trial specimens were marked with a plastic leg band, to distinguish trial specimens from natural fatalities, but without rendering the specimen unnaturally conspicuous (Smallwood 2007). To ensure a degree of “natural” placement, carcasses were tossed towards the designated, randomly chosen spot (Fig. 5). Any bird colliding with the panels is likely to slide off, down the 20° slope onto the ground as there is no lip on the lower edge, whereas birds that survive the initial impact might take shelter under the SPUs. Documentation of each location included GPS coordinates and notes about the substrate and carcass placement. Searchers moved through the area in the same manner as outlined in the standardised surveys, where specimens that were not observed, were recovered as quickly as possible to verify that carcasses had not been removed by scavengers during the trial. It should be noted that, due to the limited timeframe for the trial, searchers were aware that bird carcasses were placed on the study site. This limitation might therefore introduce a bias in the searcher efficiency results.

Carcass persistence trials

The carcass persistence trials were conducted from the 23rd of October 2015 until the 6th of December 2015 to assess the probability that a carcass persisted between search intervals. Carcass persistence is dependent on seasonal and inter-annual variation in habitat, climate, and the scavenger community (CEC and CDFG 2007, USFWS 2012, Smallwood 2013). For the purpose of this study, these factors were consistent and did not require any corrective measures as the study period represented only a single season. The trials did however estimate the influence of carcass size (Smallwood 2013). A total of 45 bird carcasses were randomly distributed and monitored among the SPUs and along the perimeter fence. This included 30 small (<100 g), 10 medium (100-1000 g), and 5 large (>1000 g) carcasses (Appendix B). Similar to the searcher efficiency trials, carcasses were tossed towards the designated, randomly chosen spot to ensure a degree of "natural" placement (Fig. 5).

In order to account for potential biases, such as scavenger swamping (Smallwood 2007, 2013), the specimens were distributed across the entire footprint of the solar farm where new specimens were placed every one to two weeks and never in excess of five individuals. All carcasses used in the trials were marked with a plastic leg band and handled with latex gloves, where the handling time was minimised to reduce the risk of leaving scent traces which may be used as cues by potential scavengers (Whelan et al. 1994). Bird carcasses were monitored per trial using Ltl-5310 ACORN motion-triggered scouting cameras and were visited on foot for the entire trial period or until the carcass disappeared or had deteriorated to a point where it would no longer qualify as a documentable fatality. GPS coordinates were taken from the specimens' locations which was visited daily for the first five days, every other day from day five to 15, and every seven days from day 15 and onwards (e.g. Ironwood Consulting 2013). Each trial specimen was classified into one of the following categories per visit (e.g. WEST 2015):

- Intact: Whole and unscavenged, other than by insects
- Scavenged/depredated: Carcass present but incomplete, dismembered, or flesh removed
- Feather spot: Carcass scavenged and removed, but sufficient feathers remain to qualify as a fatality
- Removed: Not enough remains to be considered a fatality during standard surveys

Analysis

The Huso (2011) estimator was adapted and applied to determine the total fatality at the Jasper PV facility (e.g. WEST 2015). For any arbitrary solar array *i*, the time period of three months was divided into S_i consecutive intervals of length I_{ij}, representing the total number of intervals and days per solar array. The total number of fatalities (F_{ij}) at the *i*th solar array in the *j*th interval was grouped by carcass size and search-interval category (4, 7, and 14 days), for which the probability of detection was the same for all carcasses in the set. The fatalities were calculated as the number of carcasses observed (c_{ijk}) over the probability of detection (g_{ijk}).

The probability of detection was calculated as the product of the probability of carcass persistence (r) and the probability of a carcass being observed (p), if it persist. Data from the carcass persistence trials were analysed by size class, where a chi-test was used to test significance in R version 3.2.2. The average probability of carcass persistence was estimated per size class for the given search intervals. This was applied to all birds found at the end of interval length *I*. For the searcher efficiency trials, the data were analysed by size class and the carcass' location relative to the SPU, where a standard 3×2 goodness of fit was used. The probability of a carcass being observed (p) was estimated as the number of carcasses found by searchers over the number of carcasses distributed and applied per size class and location for the given search intervals.

The total number of fatalities (F_{ijk}) was grouped into their respective sample area per search-interval category and adjusted by the proportion of the area sampled and duration of the searches per search interval. The total fatality at the Jasper PV facility was calculated as the sum of all grouped fatalities, of which 95% bootstrapped confidence intervals (CI) were estimated. Fatality rates were reported per GWh and MW.

Results

Changes in bird communities

Structural and functional differences

Over the study period, 53 bird species were recorded in and around the Jasper PV footprint of which 22 are endemic or near-endemic to southern Africa (Appendix C) and none are nationally threatened (Taylor et al. 2015). Thirty-two species were shared between the PV facility and the boundary and untransformed landscape (Fig. 6). Three species were recorded only in the development area and 15 species were recorded only in the boundary and untransformed land (Fig. 5). Based on the results, the overall density and diversity within the PV facility (38 species, 1.80 ± 0.50 birds.ha^{-1}), which is a subset of the native area, did not significantly differ ($t = -2.21$, $P = 0.06$) in comparison to the boundary (50 species, 2.63 ± 0.86 birds.ha^{-1}) and untransformed land adjacent to the boundary (47 species, 2.57 ± 0.86 birds.ha^{-1}).

The first axis of the CA, with an eigenvalue of 0.29, explains 96% of the variation in the data and differentiates the solar facility from the boundary and untransformed landscape, thereby highlighting the distribution of species among the areas (Fig. 6). Negative scores on the first axis indicate a higher presence at the solar facility such as the Cape bunting, rock martin (*Ptyonoprogne fuligula*), and Namaqua dove (*Oena capensis*). Whereas positive scores indicate a higher presence at the boundary and untransformed area such as the bokmakierie (*Telophorus zeylonus*), red-billed quelea (*Quelea quelea*), and violet-eared waxbill (*Uraeginthus granatinus*). Bird species with scores along the midpoint, such as the yellow canary, ant-eating chat (*Myrmecocichla formicivora*), and greater-striped swallow (*Hirundo cucullata*), represents an equal distribution in and around the development footprint. Since the second axis only explains 4% of the variation in the data, no definitive conclusions could further be made (Fig. 6). The results show that, there is a shift from a community preferring shrubland/woodland to one dominated by open country and grassland species, as well as those that generally associate with both habitat types and man-made structures (Fig. 6).

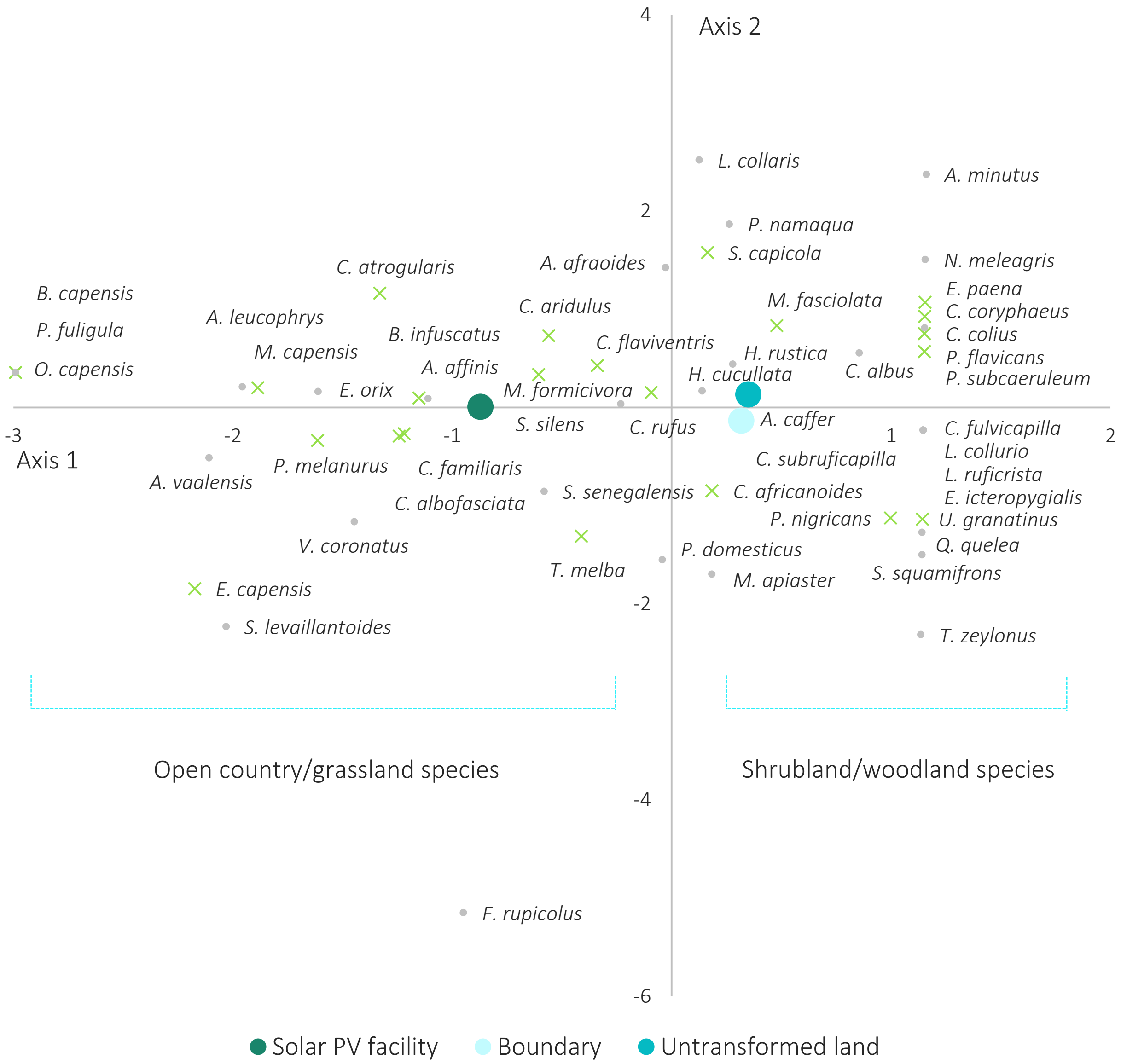


Figure 6: Biplot of the first two axes of the Correspondence Analysis (CA) representing the 53 bird species distributed over the solar facility, boundary, and untransformed landscape at the Jasper PV solar facility in the Northern Cape, South Africa. Crosses represent the 23 most abundant species within and around the development footprint, which were retained for further analysis.

The 23 most abundant bird species among the PV facility and untransformed land were retained for further analysis (Table 1). To avoid redundancy, the boundary was not included as it yielded similar results to the untransformed landscape. According to the CA-based classification, 7 species were considered to be strictly dependent on shrubland/woodland, 10 as open country/grassland and 6 as species tolerating broader habitat diversity (generalists). All shrubland/woodland species are situated under the identity straight line (y = x), signifying that they were underrepresented at the PV facility, while the open country/grassland species (75%) are located above the straight line. Most of the generalist species (67%) are found along the line itself (Fig. 7). Among the 23 studied bird species, 7 showed significant differences between their relative frequency in relation to the PV facility and untransformed landscape (Table 1), thereby revealing a higher sensitivity to the presence of the solar development than other species. It appears that shrubland/woodland species such as the black-chested prinia (*Prinia flavicans*) and chestnut-vented tit-babbler (*Parisoma subcaeruleum*) were negatively affected by the facility. In contrast, open country/grassland species and generalists were least affected, where species such as the Cape sparrow, and familiar chat (*Cercomela familiaris*) were favoured by the PV facility.

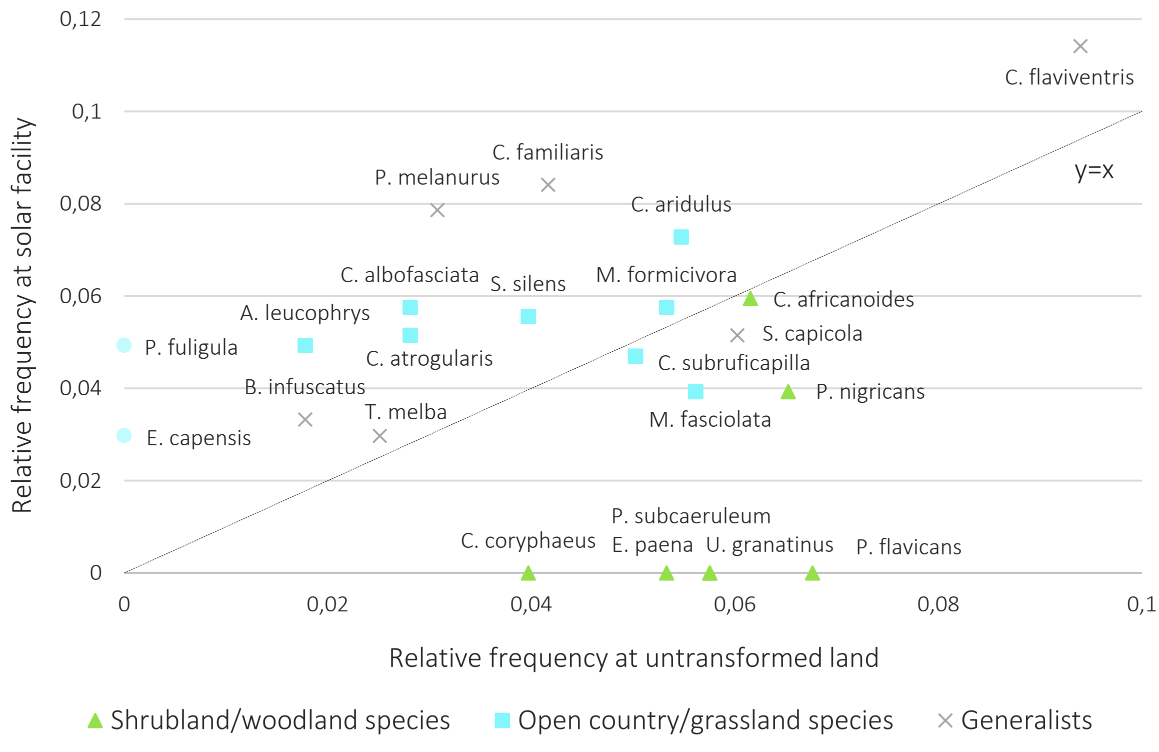


Figure 7: Comparison of relative frequencies between the Jasper PV solar facility and the untransformed landscape for each of the 23 studied species, grouped according to their habitat dependencies (Shrubland/woodland species, open country/grassland species, and generalists). The dots represent species generally associated with rocky outcrops.

Table 1: Twenty-three most abundant bird species retained for further analysis at Jasper PV solar facility in the Northern Cape South Africa. The variables N_f (D_f) and N_u (D_u) denote the species counts and density (birds.ha^{-1}) for the solar facility and untransformed landscape, respectively.

	Common name	Scientific name	N_f (D_f)	N_u (D_u)	p-value
		Shrubland/woodland species			
1	African red-eyed bulbul	*P. nigricans*	7 (NA)	25 (0.37±0.27)	n.s.
2	Black-chested prinia	*P. flavicans*	0 (NA)	29 (0.58±0.42)	<0,001
3	Chestnut-vented tit-babbler	*P. subcaeruleum*	0 (NA)	21 (0.99±0.35)	<0,001
4	Fawn-coloured lark	*C. africanoides*	16 (0.56±0.39)	24 (0.94±0.66)	n.s.
5	Kalahari scrub-robin	*E. paena*	0 (NA)	18 (0.80±0.54)	<0,001
6	Karoo scrub-robin	*C. coryphaeus*	0 (NA)	10 (0.29±0.55)	n.s.
7	Violet-eared waxbill	*U. granatinus*	0 (NA)	21 (0.62±0.98)	<0,001
		Open country/grassland			
8	Ant-eating chat	*M. formicivora*	15 (0.19±0.41)	18 (0.4±0.86)	n.s.
9	Black-throated canary	*C. atrogularis*	12 (0.52±0.59)	5 (NA)	n.s.
10	Cape bunting	*E. capensis*	4 (0.28±0.79)	0 (NA)	n.s.
11	Desert cisticola	*C. aridulus*	24 (1.27±1.21)	19 (0.5±0.31)	n.s.
12	Eastern clapper lark	*M. fasciolata*	7 (NA)	20 (0.78±0.82)	n.s.
13	Fiscal flycatcher	*S. silens*	14 (0.25±0.56)	10 (0.36±0.32)	n.s.
14	Greater-striped swallow	*C. subruficapilla*	10 (0.49±0.59)	16 (0.42±0.36)	n.s.
15	Plain-backed pipit	*A. leucophrys*	11 (0.31±0.59)	2 (NA)	n.s.
16	Rock martin	*P. fuligula*	11 (0.17±0.42)	0 (NA)	<0,01
17	Spike-heeled lark	*C. albofasciata*	15 (0.44±0.64)	5 (0.38±0.65)	n.s.
		Generalist species			
18	Alpine swift	*T. melba*	4 (0.19±0.41)	6 (NA)	n.s.
19	Cape sparrow	*P. melanurus*	28 (0.38±0.38)	6 (NA)	<0,001
20	Cape turtle dove	*S. capicola*	12 (NA)	23 (0.55±0.97)	n.s.
21	Chat flycatcher	*B. infuscatus*	5 (0.26±0.34)	2 (NA)	n.s.
22	Familiar chat	*C. familiaris*	32 (1.54±1.09)	11 (NA)	<0,01
23	Yellow canary	*C. flaviventris*	59 (0.50±0.62)	56 (0.93±0.66)	n.s.
		Total	286	347	

Figure 8: Avian use recorded during the bird community surveys at the Jasper PV solar facility in the Northern Cape, South Africa. The different areas of avian use represent (a) foraging (Orange River francolins *Scleroptila levaillantoides*), (b) hunting (rock kestrel *Falco rupicolus*), and (c) breeding (laughing dove *Spilopelia senegalensis*).

Avian use and behaviour

Several observations were made of birds using the facility as a foraging, hunting, and breeding site (Fig. 8). Vegetation regrowth between the solar arrays allowed for the presence of plant, invertebrate, and small reptile species, thereby providing a food source for the birds in the area. Several birds, including terrestrial feeders such as the Orange River francolin (*Scleroptila levaillantoides*), were observed to use the SPUs as shade and shelter, while the evaporation pond provided a drinking point for flocking species such as the Namaqua sandgrouse and scaly-feathered finch (*Sporopipes squamifrons*). Two species of raptors and one scavenger (Rock kestrel *Falco rupicolus*, pale-chanting goshawk *Melierax canorus*, and pied crow Corvus albus) were observed during the study period. The pale-chanting goshawk was mostly found at the water troughs outside of the study site and, on one occasion, at the PV facility scoping for prey. The rock kestrel was a regular visitor, observed at the evaporation pond and among the SPUs. Furthermore, eight nests of five known species were found located either directly on the mountings underneath the SPUs (n=5) or on the ground (n=3). This included the familiar chat (n=1), African red-eyed bulbul (n=1), laughing dove (*Spilopelia senegalensis*, n=1), Cape sparrow (n=2), and Cape wagtail (*Motacilla capensis*, n=1).

Collision mortality

Carcass searches

Twelve fatalities of six resident species were recorded during the study period, including one incidental (Appendix D; Table 2). The initial clearance surveys detected three of the fatalities among the SPUs and perimeter fence: One fiscal flycatcher (*Sigelus silens*), one Orange River francolin, and one African red-eyed bulbul. Thereafter, seven of the eight fatalities were detected among the SPUs, at an average rate of 0.003 birds per ha surveyed per month. The remaining fatality occurred along the fence-line at an average rate of 0.002 birds per km surveyed of fence per month. All fatalities were inferred from feather spots. Only two carcasses were found: One African red-eyed bulbul ≤2 months old, with dried flesh remains and numerous feathers, at the perimeter fence during the clearance surveys and one crowned lapwing ≤1 week old, with soft flesh remains and feathers, found incidentally next to the main road, probably due to a vehicle collision (Fig. 9).

Because no carcasses were found among the SPUs, it was impossible to assess whether impact trauma was the cause of death. There was no evidence of damaged or imprinted solar panels that might have suggested collision and since the fatalities were documented as feather spots, no further inspection could be performed. Most fatalities (n=7) were located under the SPUs, suggesting that either the birds did not collide with the upper surfaces of the panels, or they were moved by scavengers after collision. One of the fence-line fatalities (Orange River francolin) resulted from the bird being trapped between the inner and outer fence, where personnel observed the bird stunned after attempting to take flight between the fencing (Appendix D). This is further supported by observations of large-bodied birds unable to escape from between the two fences (e.g. red-crested korhaan, *Lophotis ruficrista*, n=3), except when prompted by personnel (Appendix D).

Table 2: Summary of fatalities detected during avian mortality surveys at the Jasper PV solar facility in the Northern Cape, South Africa.

Size class	Common name	Scientific name	Number detected	Total included
Small birds (<100 g)	Fiscal flycatcher	*Sigelus silens*	3[a]	2
	African red-eyed bulbul	*Pycnonotus nigricans*	1[a]	0
	Eastern clapper lark	*Mirafra apiata*	1	1
Medium birds (100-1000 g)	Orange river francolin	*Scleroptila levaillantoides*	5[a]	4
	Speckled pigeon	*Columba guinea*	1	1
	Crowned lapwing	*Vanellus coronatus*	1[b]	0
		Total	12	8[c]

[a] Fatalities detected during clearance surveys: one fiscal flycatcher, one African red-eyed bulbul, and one Orange River francolin

[b] Incidental record

[c] Fatalities included for fatality estimation (incidental and clearance survey records omitted)

Searcher efficiency trials

Searchers were able to detect 74% of the trial carcasses, where carcass size (χ^2 = 19.75, df = 2, P<0.001) and location relative to the SPUs (χ^2 = 9.26, df = 1, P<0.001) significantly influenced the probability of detection. Detection among size classes improved from 60 to 100% with increases in body mass, while location under the SPUs led to increases from 65 to 90% (Table 3).

Table 3: Results of searcher efficiency trials by size class and location of carcasses at the Jasper PV solar facility in the Northern Cape, South Africa.

	Location of carcasses detected/placed		
Size class	Adjacent to SPUs	Under SPUs	Total
Small birds (<100 g)	38/66	10/14	48/80
	58%	71%	60%
Medium birds (100-1000 g)	14/17	22/23	36/40
	82%	96%	90%
Large birds (>1000 g)	5/5	13/13	18/18
	100%	100%	100%
Total	57/88	45/50	102/138
	65%	90%	74%

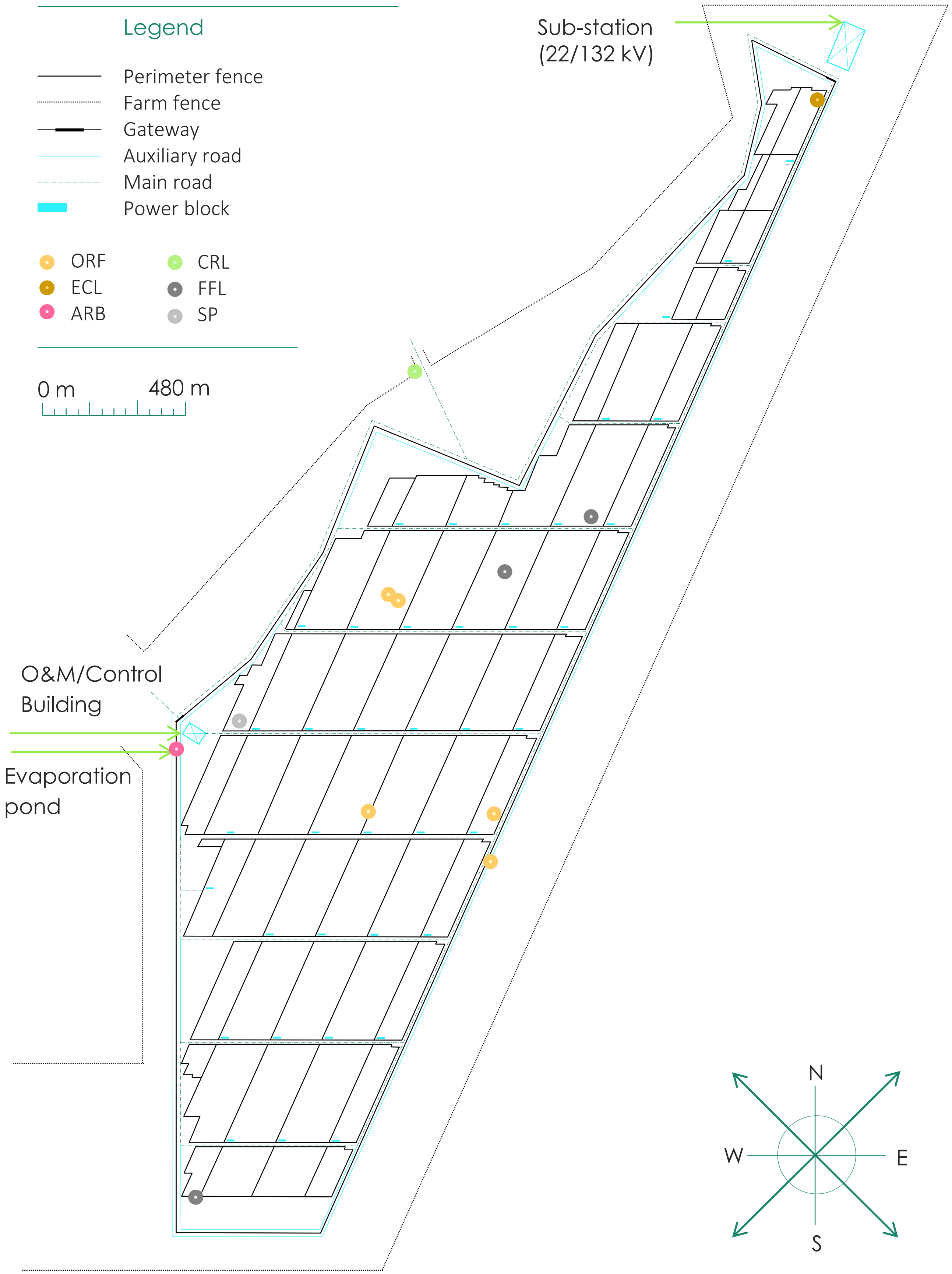
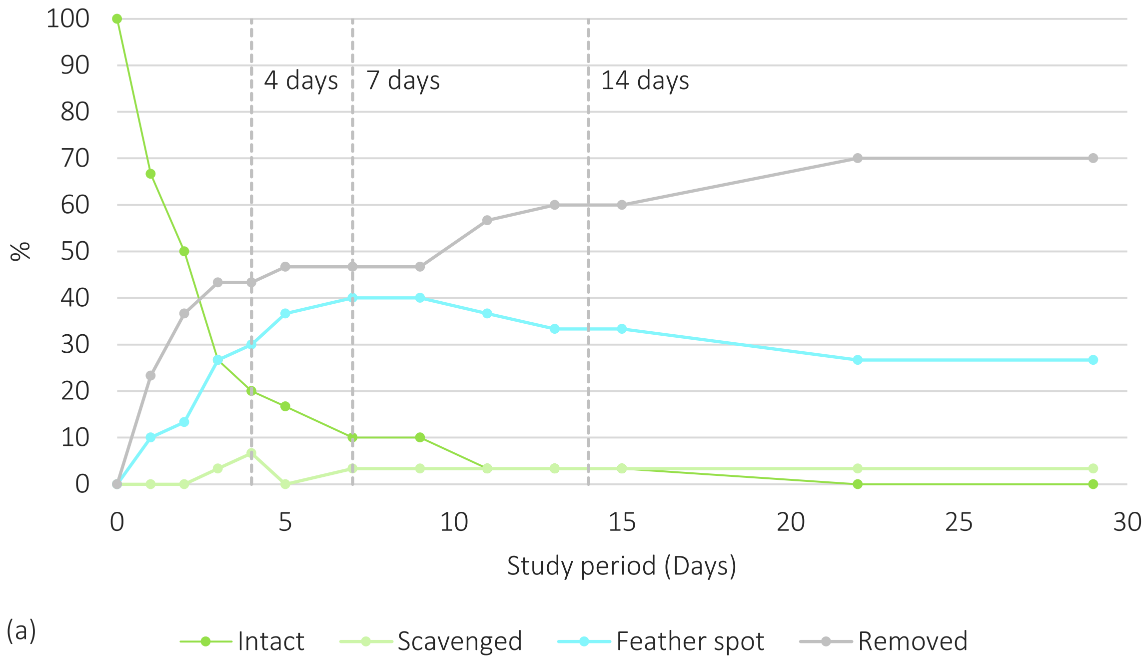


Figure 9: Distribution of avian fatalities detected, on a systematic and incidental basis, at the Jasper PV solar facility in the Northern Cape, South Africa. The 12 fatalities consists of six species, namely: Orange River francolin (ORF, *Scleroptila levaillantoides*), eastern clapper lark (ECL, *Mirafra apiata*), African red-eyed bulbul (ARB, *Pycnonotus nigricans*), crowned lapwing (CRL, *Vanellus coronatus*), fiscal flycatcher (FFL, *Sigelus silens*), and speckled pigeon (SP, *Columba guinea*).

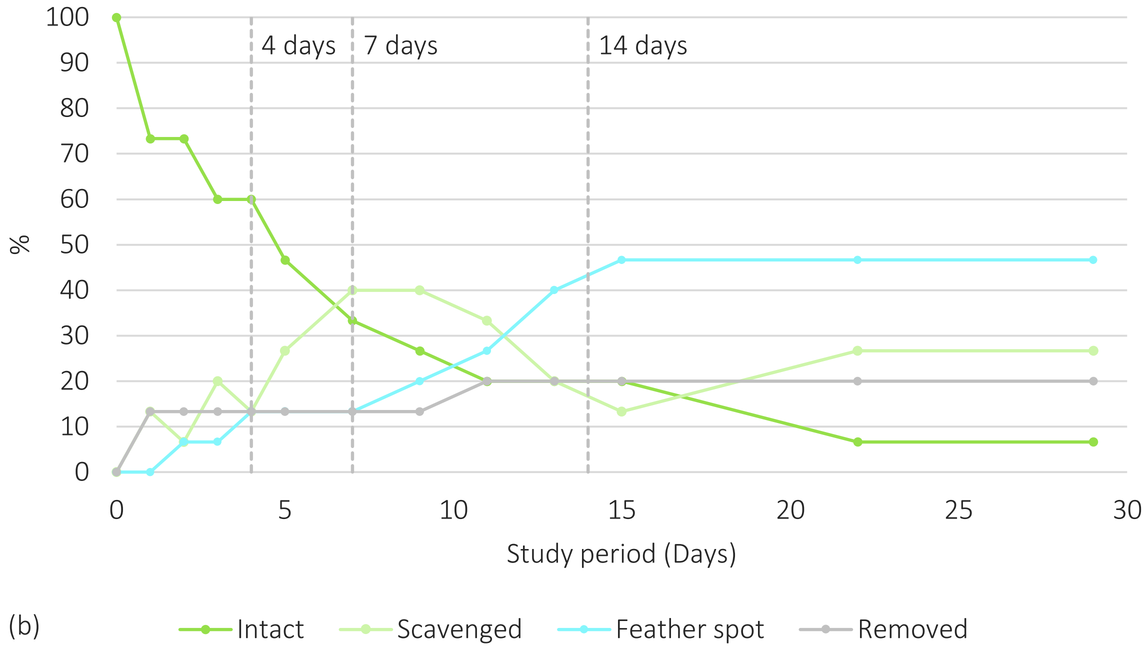
Carcass persistence trials

During the persistence trials, 80% of the carcasses could be recorded as fatalities 24 hours after placement, 64% after one week, and 47% at the end of the full trial period. Carcass size affected the likelihood of remains still being present at the end of the trial period ($\chi^2 = 8.14$, df = 1, $P<0.01$, pooling medium and large birds; Fig 10). At the given 4, 7, and 14-day search intervals, small carcasses were still detectable at 57, 53, and 40%, respectively, primarily in the form of feather spots (Fig. 10). Whereas medium/large-sized carcasses remained largely intact at 87, 87, and 80%, respectively, either as partial remains or feather spots. After three weeks, there were minor changes observed in carcass status at both size classes. Little evidence of small carcasses remained at the end of the trial period (30%) in comparison to the medium/large-sized carcasses (80%), where evidence was mainly in the form of feather spots (27 and 47%, respectively).

Based on the camera traps, small carcasses were generally removed whole by scavengers. Medium-sized carcasses were reduced to large feather spots, usually after being moved to under the SPUs. Large carcasses were mostly reduced to scattered remains, including bones and feathers, after several visits by possibly the same scavenger. Multiple feather spots were recorded from the same carcass, which remained within a 1-5 m radius from initial placement. Three species of mammal scavengers were responsible for most carcass removal: African polecats (*Ictonyx striatus*, n=4 observations), yellow mongooses (*Cynictis penicillata*, n=3), and feral cats (*Felis catus*, n=2). Other scavenger species included pied crows (n=1) and Orange River francolins (n=2). Scavenging activity appeared to be greater at night time; only yellow mongooses, pied crows, and Orange River francolins were recorded during the day.



(a)



(b)

Figure 10: Percentage of (a) small (<100 g, n=30) and (b) medium/large (>100 g, n=15) bird carcasses still detectable at increasing intervals after deployment at the Jasper PV solar facility in the Northern Cape, South Africa.

Fatality estimation

The fatality estimate for the Jasper PV facility was 435 fatalities.yr^{-1} (95% CI 133-805) over 323 920 solar panels. The annual fatality rates were 2.42 fatalities.GWh^{-1} (95% CI 0.74-4.47) over 180 GWh, 4.53 fatalities.MW^{-1} (95% CI 1.51-8.50) over 96 MW, and 2.42 fatalities.GWh^{-1} (95% CI 0.74-4.47) over 180 ha. Fatality estimates were calculated for among the SPUs from known and unknown causes, with bootstrapped 95% confidence intervals (Table 4). Due to less than 5 fatality detections for the perimeter fence, evaporation pond, power lines, and substation, individual fatality estimates were not calculated.

Table 4: Variables used per size class, search interval, and sample area to calculate the overall annual avian fatality at the Jasper PV solar facility in the Northern Cape, South Africa. This includes number detected (c), searcher efficiency (p), carcass persistence (r), and detection probability (g).

Infrastructure	Size class	Search interval	Area covered[1]	Duration	c	p	r	g
Solar panel units (SPUs)	Small	4 days	28%	31 days	1	71%	57%	40%
		7 days	28%	52 days	1	71%	53%	38%
		14 days	27%	45 days	1	71%	40%	28%
	Medium/large	4 days	28%	31 days	2	98%	87%	85%
		7 days	28%	52 days	1	98%	87%	85%
		14 days	27%	45 days	1	98%	80%	78%
Perimeter fence and evaporation pond	Small	4 days	100%	31 days	1	71%	57%	40%
		7 days	100%	52 days	0	-	-	-
		14 days	100%	45 days	0	-	-	-
	Medium/large	4 days	100%	31 days	0	-	-	-
		7 days	100%	52 days	0	-	-	-
		14 days	100%	45 days	0	-	-	-
Power lines and substation	Small	14 days	100%	52 days	0	-	-	-
	Medium/large	14 days	100%	52 days	0	-	-	-
				Total:	8			

[1] The area covered among the SPUs at sample area 1, 2, and 3 is 29920 panels (9%), 29920 panels (10%), and 29920 panels (9%), respectively, for the 4-and 7-day search interval and 24920 panels (8%), 32760 panels (10%), and 29560 panels (9%) for the 14-day search interval.
The area covered at the perimeter fence and evaporation pond at sample area 1, 2, and 3 is 4.03 km (55%), 0.65 km (9%), and 2.60 km (36%), respectively, for the 4, 7, and 14-day search interval.

Discussion and recommendations

Changes in bird communities

Structural and functional differences

In previous studies on PV developments at airports and CSP facilities in the United States, research showed that solar developments had negative impacts on the abundance and diversity of bird communities in the area, especially among the heliostat units associated with CSP (DeVault et al. 2014; Harvey & Associates 2014). Consistent with these findings, both bird density and diversity per unit area was higher in the boundary and untransformed landscape, however, the extent therefore was not considered to be as significant. This indicates that the PV facility matrix is permeable to most species. Regardless, key environmental features, including available habitat and vegetation quality are most likely the overriding factors influencing species' occurrence and their relative density within the development footprint.

There are important ecological implications behind the differences in bird assemblages between the solar facility and the untransformed landscape as these changes were non-random. It appeared that shrubland/woodland species, who were well represented amongst the untransformed landscape, were negatively affected by its development, especially species such as the black-chested prinia and chestnut-vented tit-babbler. Whether this was solely due the absence of shrubs and woody vegetation at the PV facility, is likely to be species specific. Several studies indicate that shrubland species have specific habitat requirements thereby making them specialists with narrow habitat ranges (Schlossberg & King 2008, 2009). Furthermore, shrubland birds have exhibited the tendency to either avoid or experience lower nesting success near edges of habitats or are absent or scarce in smaller habitat patches in general (King et al. 2009). This indicates that even though shrubland birds have been observed in close proximity to the PV facility, it does not necessarily represent an unaffected population. Although none of the shrubland/woodland species observed in the study area were threatened (Appendix A), the further expansion of utility-scale PV facilities might result in cumulative impacts on such bird populations. With the current lack of knowledge regarding the behavioural plasticity and habitat requirements of most species, the effect of these elements is generally difficult to predict at this time (Barrios & Rodríguez 2004; Fox et al. 2006; Madsen & Boertmann 2008). Defining fundamental life-traits in resource exploitation among species, and incorporating adequate baseline and post-construction sampling, might improve the understanding of species–landscape relationships (Lima & Zollner 1996; Fox et al. 2006).

Open country/grassland and generalist species did not appear to be adversely affected by the facility, most likely due to their ability to use both open and shrubland areas (Dean 2000; Hockey et al. 2005). Some of the species were even favoured by the PV facility, such as the Cape sparrow and familiar chat. This suggests that the area supplemented and/or complemented habitat resources for these species. Firstly, the area is dominated by short grassland on which the birds depend (Hockey et al. 2005). Secondly, some of these species are well-adapted to anthropogenic habitat disturbance and modification, with generalists benefiting from water points and built structures. Overall open country and grassland species might benefit from PV developments as the loss of open grassland habitat within the Savanna Biome has become a conservation issue. Bush encroachment has resulted in the general increase in woody vegetation at the expense of grassland and savannas across South Africa and globally, partly due to land-use change and increased carbon-dioxide levels in the atmosphere (Wigley et al. 2009, 2010; O'Connor and Chamane 2012). This has driven the range dynamics of bird species in southern Africa, leaving open country and grassland species more affected than others (Wigley et al. 2009, 2010).

Avian use and behaviour

Opposed to other constructed PV facilities, which have led to severe habitat destruction due to the complete removal of vegetation onsite (Wild Skies Ecological Services 2015), the Jasper PV facility has adopted a less intensive practice. In contrast to results from DeVault et al. (2014), the green zone created through native vegetation regrowth, and possible microclimatic changes from the PV canopies (Armstrong et al. 2014), can maintain habitat resources such as foraging, hunting, and nesting sites. In the United Kingdom, the development of PV facilities has resulted in increasing populations of wildflowers and insects (Peschel 2010; Parker & McQueen 2013). Although no vegetation and invertebrate studies have been conducted at the Jasper PV facility, a variety of species have been observed throughout the study period and may provide a food source for birds in the area. Several bird species were seen to breed at the Jasper PV facility, where most nests were located on the mountings directly underneath the solar panels. This supports the claim that some bird species, including tree-nesting species such as the African red-eyed bulbul, might use the various raised structural components as nesting and roosting sites (Lovich & Ennen 2011; Hernandez et al. 2014). However, as with other solar developments, nests are removed from the infrastructure at the study site in order to manage potential fire hazards. Finally, coinciding with a study by Feltwell (2013), raptors such as the rock kestrel have been observed to scope the corridors among the solar arrays of the Jasper PV facility. This suggests that some birds of prey have the ability to adapt to the presence of its development through the adjustment of their preying strategy. Results from boundary indicate that bird species might be unaffected by their proximity to the Jasper PV facility, where artificial structures such as the evaporation pond provide a drinking point for birds, including those that do not access the facility itself such as the red-billed quelea and white-backed mousebird (*Colius colius*).

Collision mortality

Annual fatality estimates

Upon review of existing literature, the lack of standardisation regarding data collection methods, reporting units, and bias correction at solar facilities provided for sparse and inconsistent avian-fatality data (Table 5; Walston et al. 2015). As a result, it was difficult to provide a meaningful assessment of the overall avian mortality at solar energy developments as it would lead to inaccurate extrapolations to different geographic scales and temporal periods. In relation to other energy sources, current estimates for avian mortality (collision) ranks at 5.18 (0.07) at fossil fuel, 0.416 (0.188) at nuclear, and 0.269 fatalities.GWh^{-1} at wind power facilities (Sovacool 2009). However, the extrapolated fatality estimate of 2.42 fatalities.GWh^{-1} at the study site was most likely overestimated as most fatalities were of unknown causes of death, and multiple feather spots may have resulted from one fatality. Regardless of the current limitations in fatality estimates, results imply that fossil fuels may still be more dangerous to avian wildlife than renewable energy developments.

Table 5: Summary of available avian fatality data at utility-scale solar facilities (Walston et al. 2015)

Project name (MW)	Technology	Survey period	Incidental fatalities	Systematic fatalities[a]
96 MW Jasper Solar Farm	PV(Fixed)	09/2015 to 12/2015	1	11
550 MW Desert Sunlight	PV (Fixed)	09/2011 to 03/2014	154	-
550 MW Topaz Solar Farm	PV (Fixed)	01/2013 to 01/2014	19	41
250 MW California Valley Ranch	PV (Fixed)	08/2012 to 08/2013	NA	368[b]
250 MW Mohave Solar	CSP (Trough)	08/2013 to 03/2014	14	-
250 MW Genesis	CSP (Trough)	01/2012 to 05/2014	183	8
377 MW Ivanpah	CSP (Tower)	10/2013 to 03/2014	159	376
10 MW California Solar One	CSP (Tower)	05/1982 to 05/1983	NA	70

[a] Unadjusted fatalities

[b] This value includes fatalities from known and unknown causes at all project elements including background control plots, fence lines, generation tie-line, medium voltage lines, and arrays

Similar to other studies, it is suggested that, in order to fully understand the risk of avian mortality among solar facilities and other sources of electricity generation, fatality estimates need to be calculated through standardised protocols in order to account for potential biases and provide meaningful comparisons through estimates per GWh or MW (Erickson et al. 2005; Sovacool 2009; Waltson 2015). Among solar facilities alone, fatalities per area might be a more meaningful metric, especially for estimating cumulative impacts, since the efficiency of e.g. PV panels are continuing to improve over time (Waltson et al. 2015). Metrics such as fatalities per turbine, transmission line, or solar panels per year as well as studies reporting the number of fatalities assigned to other anthropogenic sources, such as vehicles, buildings and windows, lack comparable information (Sovacool 2009). Similar to wind energy, mortality risk might be influenced by the facility's geographic setting with respect to seasonal differences in avian activity and abundance, bird migration patterns, daytime versus night time, weather patterns, and other variables such as differences in technology and size (Kuvlesky et al. 2007; Arnett et al. 2008; Harvey & Associates 2015). However, with a study period of only three months, such variables could not be investigated.

Causes of death

A comparison between solar facilities indicate that, on average, most known fatality detections were collision-related followed by predation trauma at PV and CSP (trough) facilities and solar-flux exposure at CSP (tower) facilities (Kagan et al. 2014). However, consistent with trends observed in previous monitoring programmes (Kagan et al. 2014; Waltson et al. 2015), the majority of fatalities detected during the study period were inferred from feather spots. Therefore, in the absence of evidence of bodily injuries and/or direct observations of predation or collisions, it was difficult to determine definitive causes of death at the PV facility. Further research is required to develop standardised protocols for feather spot evaluations as such fatalities may indicate lethal or nonlethal panel strikes, or simply direct mammalian or avian predation (Harvey & Associates 2015).

Impact trauma

Similar to results from DeVault et al. (2014), little evidence was found that birds using the PV arrays responded to polarised light pollution. Several design variables at the study site might have affected the illusionary characteristics of the solar arrays, which have been hypothesised to resemble a large body of water. Firstly, the Jasper PV facility implemented a 1.86 m fixed-tilt mounting system with no artificial lighting during the evening, negating the threat of tall obstacles, moving components, light pollution, or simulation of water that might result in fatalities during local movements or migration (Feltwell 2013). Secondly, the structural markings and spatial gaps on the facility's solar panels might be breaking up the reflection of the arrays (Fig. 2a). The placement of white grid lines on solar panels has reduced the attractiveness to aquatic insects, with a loss of only 1.80% in energy-producing surface as a result (Horvath et al. 2010). Although similar research is yet to be conducted on birds, the evidence from this study, and that of window collisions (Klem 1990, 2004, 2006; Loss et al. 2014), suggest that reductions in collision mortality could be achieved by 28 cm-spaced contrasting bands or 10 cm spatial gaps. This is further supported by the lack of visual markers at the Desert Sunlight and CSP facilities, creating large expanses of unobscured reflective panels and mirrors, where most collision mortality among waterbirds have been documented. Such variables may provide a visual cue for birds to differentiate the panels as a solid structure, reducing the risk of collision. If evidence of collision mortality at solar facilities continue to rise, further research into panel design should be undertaken. Modifications of utility-scale wind turbines have seen reductions in avian fatality rates (Orloff & Flannery 1992) and could be expected for improved solar panel designs.

In terms of other infrastructure, the design of the perimeter fence at the study site has resulted in large-bodied birds, such as the Red-crested korhaan, to be entrapped between the ribbon mesh and electric fence. The birds experienced difficulty escaping by flight as the gap was too narrow for their wingspan, with either electrocution or collisions between fencing as a result. This was further supported by the injury of the Orange River francolin at the perimeter fence, where personnel observed the bird stunned after attempting to take flight between the fencing (Appendix D). However, these events are considered to be site-specific as fatalities at other solar facilities, with single-fence designs, were sufficiently low and unrelated to the study site (e.g. Harvey & Associates 2015). In contrast to monitoring programmes at other solar facilities, no fatalities were documented among the power lines, substation, or evaporation pond, most likely due to the relative absence of large-bodied birds that are vulnerable to collision with such infrastructure and/or the short period in which surveys in this study were conducted.

Stranding and predation

It is anticipated that a proportion of the unknown fatalities at the study site is the result of predation associated with non-fatal impact trauma with the solar panels, or other causes unrelated to

PV facility. This is supported by the observations of large-bodied birds such as the Orange River francolin colliding with the underside of the SPUs (Appendix D). When flushed, quick navigation through the high-clutter environment of panels resulted in the collision into structural elements of the array, thereby potentially leaving them vulnerable against opportunistic predators. Observations at other solar facilities supports this assertion of non-fatal collisions through evidence of predation mortalities among water-dependent species. The studies report that attempts to land on the solar panels may have either injured or stranded the birds, rendering them unable to escape to safety or easily take-off from land (Kagan et al. 2014). In this situation, although the cause of death is only indirectly related to the presence of the panels, it would still be classified as a solar-related collision.

Monitoring limitations

Similar to the wind industry (Warren-Hicks et al. 2013), challenges to monitoring success included variations in carcass detection by size class and location relative to the SPU. Searcher efficiency indicated that small carcasses would be more difficult to detect than larger-sized carcasses during surveys as well as carcasses located adjacent to the SPUs. This was most likely due to a denser vegetation cover, in comparison to the area under the SPUs, with the orientation of the panels further obscuring ground visibility. The persistence trials confirmed that the rates of carcass removal were greatest in the first week with negligible removal rates surpassing three weeks after placement. Most carcasses were removed within four weeks. Removal rates were higher for small bird carcasses most likely because they are more easily to remove from the development area by scavengers. Scavenger activity appeared not to be affected by the perimeter fence at the study site as terrestrial scavengers such as the yellow mongoose moved effortlessly through the ribbon mesh fence, while larger scavengers dug a swallow hole under the fence as it was not embedded deep into the ground.

This underlines the need for accounting covariates in the searcher efficiency and carcass persistence trials at solar facilities, where results from this study points to shorter intervals in order to maximise the chance of detecting a carcass. There may be limited value in sampling every three weeks or more, therefore, search intervals of no more than two weeks is recommended in post-monitoring research. In order to further improve the probability of carcass detection, protocols should include the placement of feather spots as the probability of detection varied significantly based on findings at the Ivanpah CSP facility (Harvey & Associates 2015). Furthermore, if resources allow, canine searcher efficiency trials should be incorporated in the protocols since have indicated improved detection rates for carcasses and feather spots (Harvey & Associates 2015).

Residency and species composition

Results from the bird community surveys indicated that open country/grassland and generalist species were most abundant within the development footprint and, therefore, used the facility more extensively than others. Although the sample size of fatality detections was too small for conclusive findings, most of the observed fatalities were of species overrepresented at the PV facility such as the fiscal flycatcher and eastern clapper lark. In addition, consistent with results from other solar facilities, resident species and passerines represent most of the avian mortality at the study site (Waltson et al. 2015) as such species were more prevalent within and around the development footprint. Even though water-dependent bird species could potentially occur in the study area (Appendix A), they were underrepresented at the PV facility, with only two flocks of spur-winged goose (*Plectropterus gambensis*) observed to fly-over during the study period. This indicates that, similar to studies in the wind industry, the level of bird use and behaviour of birds at the site could be important factors to consider when assessing potential risk at solar facilities and should be incorporated in future research and monitoring programmes (Erickson et al. 2002; Anderson et al. 2004; Kingsley and Whittam 2007; Kuvlesky et al. 2007).

Conclusion

This study demonstrated that, although some results still remain inconclusive, the concerns regarding the direct impacts of utility-scale PV developments on bird populations and communities are not entirely unfounded. The distribution of birds in the landscape altered in response to changes in the distribution and abundance of habitat resources such as food, water and nesting sites, which altered resource availability patterns that were beneficial to some bird species and detrimental to others. Shrubland/woodland species were threatened by the land-use changes associated with its development, potentially resulting in effective and/or physical habitat loss (Fox et al. 2006). Open country/grassland and generalist species were favoured by its presence with PV developments potentially offsetting some of the widespread loss among these species due to bush encroachment, which has led to increases in shrub-dependent species at the expense of open country and grassland birds. Due to the monitoring limitations, no definitive link with collision impact trauma could be found with solar-related infrastructure at the PV facility. However, finding few carcasses that can be assigned to a conclusive cause of death does not necessarily rule out the possibility of avian mortality. While any bird flying over the solar facility, or using it extensively, is at risk of collision, the extent thereof will most likely depend on biological, topographical, meteorological and technical factors (Bevanger 1994, 1998; Shaw et al. 2010; Lovich & Ennen 2011).

The impact of solar energy development on bird populations must be viewed in the context of climate change in the absence of the solar industry. Continued reliance on fossil-fuel consumption may result in global costs to bird populations that vastly outweigh any effects of the industry. Therefore, the apparent negative impacts of solar PV development should not hamper efforts aimed at reconciling increases in renewable energy generation with wildlife conservation. Similar to other energy sources, the impact of PV facilities on birds is likely to differ on a case-by-case basis (Lovich & Ennen 2011), where solar developments replacing previously degraded lands, such as old landfills or agricultural sites, can play an important role in promoting biodiversity (Peschel 2010; Parker & McQueen 2013). The opposite is generally the case with developments carved out of pristine or near-pristine habitats. Combined with results from other studies (Peschel 2010; Parker & McQueen 2013; DeVault et al. 2014), utility-scale PV facilities can offer opportunities for climate protection that do not conflict with nature conservation. Furthermore, the various forms of PV energy generation such as roof-top structures and other distributed solar sources would have lower impacts while providing the same CO_2 reduction benefits.

The results of this study suggests that on-site minimisation measures should be carried out under an adaptive management framework in order to assess their effectiveness before broad-scale applications are used. For the solar industry, the participation in research addressing wildlife impact challenges in the early stages of the energy sector's growth may help avoid situations that the wind industry experienced, in which informative research was delayed or conducted under research designs that did not adequately address the issues at hand (Fox et al. 2006; Stewart 2007; Waltson et al. 2015). Therefore, building upon lessons learned, there is a need for the collation and analysis of data from solar energy facilities across spatial and temporal scales and to produce comparable results from different energy sources. Scientifically rigorous survey, monitoring, assessment, and research designs will fill the gaps regarding the industry, thereby allowing the compilation of appropriate mitigation protocols to alleviate any adverse effects on species of concern and their habitats (Waltson et al. 2015).

Acknowledgements

I would first and foremost like to thank my main supervisor, Prof. Peter Ryan for his insightful comments and constructive criticisms as they were thought-provoking and helped me find clarity among my ideas. I would also like to thank my co-supervisor Samantha Ralston from BirdLife South Africa for making this thesis possible and Alvaro Cardenal from Universidad Complutense for all his advice and swift replies to any questions that I had. Most importantly, I am grateful for my supervisors to take time out of their busy schedules in order to come through to the Northern Cape to lend a hand with my searcher efficiency trials and allowing me to accompany them on visits to the variety of solar energy facilities in South Africa. It has been an eye-opening experience. I would also like to acknowledge SolarReserve for allowing me to conduct my research at one of their solar facilities and the Percy FitzPatrick Ornithological Institute for not only funding the thesis, but also providing the necessary resources for my project. A very special thanks to Paul and Annelien Ferreira as well as a special group of people at the Jasper solar energy project for their immense hospitality during my stay in Owendale and for expressing such a genuine interest in my work. At the end of the day, none of this would have been possible without the support and patience of my family and loved ones to whom I will forever be grateful. Finally, I consider myself extremely privileged to have been part of the 2015 Conservation Biology course and spending my year with a formidable group of people. Their infectious enthusiasm and ability to laugh throughout the long nights and stressful times has made this an unforgettable experience.

Literature cited

Anderson, M.D. 2001. The effectiveness of two different marking devices to reduce large terrestrial bird collisions with overhead electricity cables in the eastern Karoo, South Africa. Draft report to Eskom Resources and Strategy Division, Johannesburg.

Anderson, R.L., N. Neumann, J. Tom, W.P. Erickson, M.D. Strickland, M. Bourassa, K.J. Bay, and K.J. Sernka. 2004. Avian Monitoring and Risk Assessment at the Tehachapi Pass Wind Resource Area: Period of Performance: October 2, 1996–May 27, 1998. Unpublished report to National Renewable Energy Laboratory, California.

Armstrong, A., J. Waldron, J. Whitaker, and N.J. Ostle. 2014. Wind farm and solar park effects on plant–soil carbon cycling: uncertain impacts of changes in ground-level microclimate. Global Change Biology DOI: 10.1111/gcb.12437.

Arnett, E.B., W.K. Brown, W.P. Erickson, J.K. Fiedler, B.I. Hamilton, T.H. Henry, A. Jain, G.D. Johnson, J. Kerns, R.R. Koford, C.P. Nicholson, T.J. O'Connell, M.D. Piorkowski, and R.D. Tankersley Jr. 2008. Patterns of Bat Fatalities at Wind Energy Facilities in North America. Journal of Wildlife Management **72**: 61-78.

Barrios, L. and A. Rodríguez. 2004. Behavioural and environmental correlates of soaring-bird mortality at on-shore wind turbines. Journal of Applied Ecology **41**: 72-81.

Bevanger, K. 1994. Bird interactions with utility structures: collision and electrocution, causes and mitigating measures. Ibis **136**: 412-425.

Bevanger, K. 1998. Biological and conservation aspects of bird mortality caused by electric power lines. Biological Conservation **86**: 67-76.

Bibby, C.J, N.D. Burgess, D.A. Hill, and S.H. Mustoe. 2000. Bird Census Techniques: 2nd edition. Academic Press, London.

Buckland, S.T., D.R. Anderson, K.P. Burnham, J.L. Laake, D.L. Borchers, and L. Thomas. 2001. Introduction to Distance Sampling. Oxford: Oxford University Press.

Caplat, P. and J. Fonderflick. 2009. Area mediated shifts in bird community composition: a study on a fragmented Mediterranean grassland. Biodiversity Conservation **18**: 2979-2995.

CEC (California Energy Commission) and CDFG (California Department of Fish and Game). 2007. California Guidelines for Reducing Impacts to Birds and Bats from Wind Energy Development: Commission Final Report. CEC, Renewables Committee, and Energy Facilities Siting Division, and CDFG, Resources Management and Policy Division, Sacramento.

Dean, W.R.J. 2000. Factors affecting bird diversity patterns in the Karoo, South Africa. South African Journal of Science **96**: 609–616.

DeVault, T.L., T.W. Seamans, J.A. Schmidt, J.L. Belant, B.F. Blackwell, N. Mooers, L.A. Tyson, and L. Van Pelt. 2014. Bird use of solar photovoltaic installations at US airports: Implications for aviation safety. Landscape and Urban Planning **122**: 122-128.

DoE (Department of Energy). 2015. State of Renewable energy in South Africa. Department of Energy, Pretoria.

Drewitt, A.L. and R.H.W. Langston. 2008. Collision effects of wind-power generators and other obstacles on birds. Annals of the New York Academy of Sciences **1134**: 233-266.

Eberhard, A., J. Kolker, and J. Leigland. 2014. South Africa's Renewable Energy IPP Procurement Programme: Success Factors and Lessons. PPIAF, Washington, D.C.

Erickson, W.P., G.D. Johnson, D.P. Young Jr., M.D. Strickland, R. Good, M. Bourassa, K. Bay, and K. Sernka. 2002. Synthesis and Comparison of Baseline Avian and Bat Use, Raptor Nesting and Mortality Information from Proposed and Existing Wind Developments. Unpublished report to Bonneville Power Administration, Portland.

Erickson, W.P., G.D. Johnson, and D.P. Young Jr. 2005. A summary and comparison of bird mortality from anthropogenic causes with an emphasis on collisions. General technical report to USDA Forest Service, Cheyenne.

ERM (Environmental Resources Management). 2011. Final Environmental Impact Report: Proposed Humansrus PV 2 Solar Power Farm, Northern Cape. Unpublished report to Intikon Energy, Cape Town.

Feltwell, J. 2013. Are photovoltaic solar arrays an influencing factor in avian mortality? Newsletter of the Kent Field Club, Kent.

Fox, A.D., J. Kahlert, T.K. Christensen, and I.K. Petersen. 2006. Information needs to support environmental impact assessment of the effects of European marine offshore wind farms on birds. Ibis **148**: 129-144.

Gauthreaux, S.A. and C.G. Belser. 2006. Effects of artificial night lighting on migrating birds. Pages 67-93 in C. Rich and T. Longcore Ecological Consequences of Artificial Night Lighting, 1st edition. Island Press, Washington, D.C.

Burck, J., F. Marten, and C. Bals. 2015. Climate Change Performance Index: Results 2015. Germanwatch and Climate Action Network Europe, Berlin.

Gunerhan, H., A. Hepbasli, and U. Giresunli. 2009. Environmental impacts from the solar energy systems. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects **31**: 131-138.

Harvey and Associates. 2014. California Valley Solar Ranch Project avian and bat protection plan: Quarterly post-construction fatality report, 16 November 2013 - 15 February 2014. Unpublished report to HPR II, PLC, California Valley Solar Ranch, San Luis Obispo.

Harvey and Associates. 2015. Ivanpah solar electric generating system avian and bat protection plan: 2013-2014 annual report. Unpublished report to HPR II, PLC, Ivanpah Solar Energy, Fresno.

Hernandez, R.R., S.B. Easter, M.L. Murphy-Mariscal, E.T. Maestre, M. Tavassoli, E.B. Allen, C.W. Barrows, J. Belnap, R. Ochoa-Hueso, S. Ravi, and M.F. Allen. 2014. Environmental impacts of utility-scale solar energy. Renewable & Sustainable Energy Reviews **29**: 766-779.

Hockey, P.A.R., W.R.J. Dean, and P.G. Ryan. 2005. Roberts - Birds of southern Africa, Seventh edition. The Trustees of the John Voelcker Bird Book Fund, Cape Town.

Horváth, G., G. Kriska, P. Malik, and B. Robertson. 2009. Polarized light pollution: a new kind of ecological photopollution. Frontiers in Ecology and the Environment **7**: 317-325.

Horváth, G., M. Blahó, A. Egri, G. Kriska, I. Seres, and B. Robertson. 2010. Reducing the maladaptive attractiveness of solar panels to polarotactic insects. Conservation Biology **24**: 1644-1653.

Huso, M.M.P. 2011. An estimator of wildlife fatality from observed carcasses. Environmetrics **22**: 318-329.

Ironwood Consulting. 2013. Bird and bat conservation plan Silver State Solar Power South: BLM case file numbers: nvn-089530, nvn-085801 Clark County, Nevada. Unpublished report to BLM, Silver State Solar Power South, Redlands.

Janss, G.F.E. 2000. Avian mortality from power lines: a morphologic approach of a species-specific mortality. Biological Conservation **95**: 353-359.

Jenkins, A.R., J.J. Smallie, and M. Diamond. 2010. Avian collisions with power lines: a global review of causes and mitigation with a South African perspective. Bird Conservation International **20**:263-278.

Kagan, R.A., T.C. Viner, P.W. Trail, and E.O. Espinoza. 2014. Avian Mortality at Solar Energy Facilities in Southern California: A Preliminary Analysis. Unpublished report to US National Fish and Wildlife Forensic Laboratory, Ashland.

King, D. I., R. B. Chandler, S. Schlossberg, and C.C. Chandler. 2009. Habitat use and nest success of scrub-shrub birds in wildlife and silvicultural openings in western Massachusetts, U.S.A. Forest Ecology and Management **257**: 421-426.

Kingsley, A. and B. Whittam. 2007. Wind Turbines and Birds: A Background Review for Environmental Assessment. Unpublished report to Environment Canada/Canadian Wildlife Service, Quebec.

Klem, D. 1990. Collisions between birds and windows: mortality and prevention. Journal of Field Ornithology **61**: 120-128.

Klem, D., D.C. Keck, K.L. Marty, A.J. Miller Ball, E.E. Niciu, and C.T. Platt. 2004. Effects of window angling, feeder placement, and scavengers on avian mortality at plate glass. Wilson Bulletin **116**: 69-73.

Klem, D. 2006. Glass: A deadly conservation issue for birds. Bird Observer **34**: 73-81.

Korner-Nievergelt, F., P. Korner-Nievergelt, O. Behr, I. Niermann, R. Brinkmann, and B. Hellriegel. 2011. A new method to determine bird and bat fatality at wind energy turbines from carcass searches. Wildlife Biology **17**: 350-363.

Krijgsveld, K.L., K. Akershoek, F. Schenk, F. Dijk, S. Dirksen. 2009. Collision risk of birds with modern large wind turbines. Ardea **97**: 357-366.

Kuvlesky, W.P., L.A. Brennan, M.L. Morrison, K.K. Boydston, B.M. Ballard, and F.C. Bryant. 2007. Wind energy development and wildlife conservation: Challenges and opportunities. Journal of Wildlife Management **71**: 2487-2498.

Lehman, R.N., P.L. Kennedy, and J.A. Savidge. 2007. The state of the art in raptor electrocution research: a global review. Biological Conservation **136**: 159-174.

Lima, S.L. and P.A. Zollner. 1996. Towards a behavioural ecology of ecological landscape. Trends in Ecology & Evolution **11**: 131–135.

Loss, S.R., T. Will, S.S. Loss, and P.P. Mara. 2014. Bird-building collisions in the United States: Estimates of annual mortality and species vulnerability. Condor **116**: 8-23.

Lovich, J.E. and J.R. Ennen. 2011. Wildlife conservation and solar energy development in the desert southwest, United States. BioScience **61**: 982-992.

Madsen, J. and D. Boertmann. 2008. Animal behavioral adaptation to changing landscapes: Spring-staging geese habituate to wind farms. Landscape Ecology **23**: 1007-1011.

McCrary, M.D., R.L. McKernan, R.W. Schreiber, W.D. Wagner, and T.C. Sciarrotta. 1982. Avian mortality at a solar energy power plant. Journal of Field Ornithology **57**: 135-141.

Morrison, M. 2002. Searcher bias and scavenging rates in bird/wind energy studies: National Renewable Energy Report SR-500-30876. National Renewable Energy Laboratory, Bishop.

Mucina, L. and M.C. Rutherford. 2006. The vegetation of South Africa, Lesotho and Swaziland. Strelitzia **19**: 540-567. South African National Biodiversity Institute, Pretoria.

O'Connor, T.G. and S.C. Chamane. 2012. Bush clump succession in grassland in the Kei Road region of the Eastern Cape, South Africa. African Journal of Range and Forage Science **29**: 133−146.

Orloff, S. and A. Flannery. 1992. Wind Turbine Effects on Avian Activity, Habitat Use, and Mortality in Altamont Pass and Solano County Wind Resource Areas, 1989-1991. Final Report. P700-92-001. Unpublished report to Planning Departments of Alameda, Contra Costa and Solano Counties and the California Energy Commission, Sacramento.

Parker, G.E. and C. McQueen. 2013. Can solar farms deliver significant benefits for biodiversity? Preliminary Study July-August 2013. Unpublished report to Rowsell & McQueen, Bishop.

Pearce-Higgins, J.W. and M.C. Grant. 2006. Relationship between bird abundance and the composition and structure of moorland vegetation. Bird Study **53**: 112-115.

Peschel, T. 2010. Solar parks – Opportunities for biodiversity: A report on biodiversity in and around ground-mounted photovoltaic plants. German Renewable Energies Agency, Berlin.

Phillips, J. 2013. Determining the sustainability of large-scale photovoltaic solar power plants. Renewable & Sustainable Energy Reviews **27**: 435-444.

Reinkensmeyer, J.W., R.F. Miller, R.G. Anthony, V.E. Marr, and C.M. Duncan. 2008. Winter and early spring bird communities in grasslands, shrubsteppe, and juniper woodlands in Central Oregon. Western North American Naturalist **68**: 25-35.

SABAP2 (Second Southern African Bird Atlas Project). 2015. Southern African Bird Atlas Project. Available from http://sabap2.adu.org.za/ (accessed January 2016).

Schlossberg, S.R. and D.I. King. 2009. Postlogging Succession and Habitat Usage of Shrubland Birds. Journal of Wildlife Management **73**: 226-231.

Schlossberg, S.R. and D.I. King. 2008. Are shrubland birds edge-specialists? Ecological Applications **18**: 1325–1330.

Shaw, J.M., A.R. Jenkins, J.J. Smallie, and P.G. Ryan. 2010. Modelling power-line collision risk for the Blue Crane *Anthropoides paradiseus* in South Africa. Ibis **152**: 590-599.

Smallwood, K.S. 2007. Estimating wind turbine-caused bird mortality. Journal of Wildlife Management **71**: 2781–2791.

Smallwood, K.S. 2013. Comparing bird and bat fatality-rate estimates among North American wind-energy projects. Wildlife Society Bulletin **37**: 19-33.

Sovacool, B.K. 2009. Contextualizing avian mortality: A preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity. Energy Policy **37**: 2241–2248.

Stewart, G.B., A.S. Pullin, and C.F. Coles. 2007. Poor evidence-base for assessment of windfarm impacts on birds. Environmental Conservation **34**: 1–11.

Strickland M., E.B. Arnett, W.P. Erickson, D.H. Johnson, G.D. Johnson, M.L. Morrison, J.A. Shaffer, and W. Warren-Hicks. 2011. Comprehensive guide to studying wind energy/wildlife interactions. National Wind Coordinating Collaborative, Washington, D.C.

Taylor, M.R., F. Peacock, and R.M. Wanless. 2015. The 2015 Eskom Red Data Book of birds of South Africa, Lesotho, and Swaziland. BirdLife South Africa, Johannesburg.

Thomas, L., S.T. Buckland, E.A. Rexsted, J.L. Laake, S. Strindberg, S.L. Hedley, J.R.B. Bishop, T.A. Marques, and K.P. Burnham. 2010. Distance software: design and analysis of distance sampling surveys for estimating population size. Journal of Applied Ecology **47**: 5-14.

Tsoutsos, T., N. Frantzeskaki, and V. Gekas. 2005. Environmental impacts from solar energy technologies. Energy Policy **33**: 289-296.

Turney, D. and V. Fthenakis. 2011. Environmental impacts from the installation and operation of large-scale solar power plants. Renewable and Sustainable Energy Reviews **15**: 3261-3270.

USFWS (US Fish and Wildlife Service). 2012. Final Land-Based Wind Energy Guidelines. USFWS, Arlington.

Waltson, L.J., K.E. Rollins, K.P Smith, K.E. LaGory, K. Sinclair, C. Turchi, T. Wendelin, and H. Souder. 2015. A Review of Avian Monitoring and Mitigation Information at Existing Utility-Scale Solar Facilities. Unpublished report to Environmental Science Division, Argonne National Laboratory, Argonne.

Warren-Hicks, W., J. Newman, R. Wolpert, B. Karas, and L. Tran. 2013. Improving methods for estimating fatality of birds and bats at wind energy facilities. Unpublished report to California Energy Commission, Berkeley.

WEST (Western EcoSystems Technology, Inc.). 2015. Bird and Bat Conservation Strategy Genesis Solar Energy Project - Riverside County, California. Western EcoSystems Technology, Cheyenne.

Whelan, C.J., M.L. Dilger, D. Robson, N. Hallyn, and S. Dilger. 1994. Effects of olfactory cues on artificial-nest experiments. Auk **111**: 945–952.

Wigley, B.J., W.J. Bond, and M.T. Hoffmann. 2009. Bush encroachment under three contrasting land-use practices in a mesic South African savanna. African Journal of Ecology **47**: 62–70.

Wigley, B.J., W.J. Bond, and M.T. Hoffmann. 2010. Thicket expansion in a South African savanna under divergent land use: local versus global drivers? Global Change Biology **16**: 964–976.

Wild Skies Ecological Services. 2015. 11 Solar PV Facilities and Supporting Electrical Infrastructure near Dealesville in the Free State Province Proposed by Mainstream Renewable Power Developments (Pty) Ltd. Unpublished report to CSIR, Dealesville.

Appendix A: Comprehensive SABAP2 list of bird species that might occur within the study area at the Jasper PV solar facility in the Northern Cape, South Africa. Bird species are defined based on conservation status and endemism in southern Africa and their susceptibility to anthropogenic disturbances (Taylor et al. 2015; SABAP2 2015).

Common name	Scientific name	Conservation status	Regional endemism	Susceptibility to		
				Collision	Electrocution	Disturbance /habitat loss
Black harrier	*Circus maurus*	Endangered	Endemic	-	-	Moderate
Martial eagle	*Polemaetus bellicosus*	Endangered	-	Moderate	High	Moderate
Tawny eagle	*Aquila rapax*	Endangered	-	-	High	Moderate
Black stork	*Ciconia nigra*	Vulnerable	-	High	Moderate	-
White-backed vulture	*Gyps africanus*	Vulnerable	-	High	Moderate	-
Secretarybird	*Sagittarius serpentarius*	Vulnerable	-	High	-	Moderate
Blue crane	*Anthropoides paradiseus*	Near-threatened	Endemic	High	-	Moderate
Kori bustard	*Ardeotis kori*	Near-threatened	-	High	-	Moderate
Greater flamingo	*Phoenicopterus roseus*	Near-threatened	-	High	-	-
Northern black korhaan	*Afrotis afraoides*	-	Endemic	Moderate	-	Moderate
South african shelduck	*Tadorna cana*	-	Endemic	High	-	-
Cape shoveler	*Anas smithii*	-	Endemic	Moderate	-	-
Ant-eating chat	*Myrmecocichla formicivora*	-	Endemic	-	-	Moderate
Fairy flycatcher	*Stenostira scita*	-	Endemic	-	-	Moderate
Fiscal flycatcher	*Sigelus silens*	-	Endemic	-	-	Moderate
Eastern long-billed Lark	*Certhilauda semitorquata*	-	Endemic	-	-	Moderate
Karoo long-billed Lark	*Certhilauda subcoronata*	-	Endemic	-	-	Moderate
White-backed mousebird	*Colius colius*	-	Endemic	-	-	Moderate
Karoo scrub-robin	*Cercotrichas coryphaeus*	-	Endemic	-	-	Moderate
Karoo thrush	*Turdus smithi*	-	Endemic	-	-	Moderate
Rufous-eared warbler	*Malcorus pectoralis*	-	Endemic	-	-	Moderate

Sociable weaver	*Philetairus socius*	-	Endemic	-	-	Moderate
Orange River white-eye	*Zosterops pallidus*	-	Endemic	-	-	Moderate
Orange River francolin	*Scleroptila levaillantoides*	-	Near-endemic	Moderate	-	Moderate
Southern pale chanting goshawk	*Melierax canorus*	-	Near-endemic	-	Moderate	Moderate
Red-crested korhaan	*Lophotis ruficrista*	-	Near-endemic	Moderate	-	Moderate
Southern yellow-billed hornbill	*Tockus leucomelas*	-	Near-endemic	Moderate	-	-
Acacia pied barbet	*Tricholaema leucomelas*	-	Near-endemic	-	-	Moderate
Pririt batis	*Batis pririt*	-	Near-endemic	-	-	Moderate
Bokmakierie	*Telophorus zeylonus*	-	Near-endemic	-	-	Moderate
African red-eyed bulbul	*Pycnonotus nigricans*	-	Near-endemic	-	-	Moderate
Cape bunting	*Emberiza capensis*	-	Near-endemic	-	-	Moderate
Lark-like bunting	*Emberiza impetuani*	-	Near-endemic	-	-	Moderate
White-throated canary	*Crithagra albogularis*	-	Near-endemic	-	-	Moderate
Yellow canary	*Crithagra flaviventris*	-	Near-endemic	-	-	Moderate
Grey-backed cisticola	*Cisticola subruficapilla*	-	Near-endemic	-	-	Moderate
Red-headed finch	*Amadina erythrocephala*	-	Near-endemic	-	-	Moderate
Scaly-feathered finch	*Sporopipes squamifrons*	-	Near-endemic	-	-	Moderate
Chat flycatcher	*Bradornis infuscatus*	-	Near-endemic	-	-	Moderate
Marico flycatcher	*Bradornis mariquensis*	-	Near-endemic	-	-	Moderate
Eastern clapper lark	*Mirafra fasciolata*	-	Near-endemic	-	-	Moderate
Fawn-coloured Lark	*Calendulauda africanoides*	-	Near-endemic	-	-	Moderate
Cape penduline-tit	*Anthoscopus minutus*	-	Near-endemic	-	-	Moderate
Short-toed rock-thrush	*Monticola brevipes*	-	Near-endemic	-	-	Moderate
Kalahari scrub-robin	*Erythropygia paena*	-	Near-endemic	-	-	Moderate
Cape sparrow	*Passer melanurus*	-	Near-endemic	-	-	Moderate
Great sparrow	*Passer motitensis*	-	Near-endemic	-	-	Moderate
Pale-winged starling	*Onychognathus nabouroup*	-	Near-endemic	-	-	Moderate
Dusky sunbird	*Cinnyris fuscus*	-	Near-endemic	-	-	Moderate

Ashy tit	*Parus cinerascens*	-	Near-endemic	-	-	Moderate
Chestnut-vented tit-babbler	*Parisoma subcaeruleum*	-	Near-endemic	-	-	Moderate
Violet-eared waxbill	*Uraeginthus granatinus*	-	Near-endemic	-	-	Moderate
Mountain wheatear	*Oenanthe monticola*	-	Near-endemic	-	-	Moderate
Shaft-tailed whydah	*Vidua regia*	-	Near-endemic	-	-	Moderate
Burchell's courser	*Cursorius rufus*	-	Near-endemic	-	-	-
Namaqua sandgrouse	*Pterocles namaqua*	-	Near-endemic	-	-	-
Verreaux's eagle	*Aquila verreauxii*	-	-	Moderate	High	Moderate
Egyptian goose	*Alopochen aegyptiacus*	-	-	High	High	-
Spur-winged goose	*Plectropterus gambensis*	-	-	High	Moderate	-
Spotted eagle-owl	*Bubo africanus*	-	-	-	High	Moderate
Helmeted guineafowl	*Numida meleagris*	-	-	Moderate	-	High
Black-headed heron	*Ardea melanocephala*	-	-	Moderate	Moderate	-
Grey heron	*Ardea cinerea*	-	-	Moderate	Moderate	-
Lesser kestrel	*Falco naumanni*	-	-	Moderate	-	Moderate
Steppe buzzard	*Buteo vulpinus*	-	-	-	Moderate	Moderate
Barn owl	*Tyto alba*	-	-	-	Moderate	Moderate
Black-chested snake-eagle	*Circaetus pectoralis*	-	-	-	Moderate	Moderate
White-breasted cormorant	*Phalacrocorax lucidus*	-	-	Moderate	-	-
African black duck	*Anas sparsa*	-	-	Moderate	-	-
Maccoa duck	*Oxyura maccoa*	-	-	Moderate	-	-
White-faced duck	*Dendrocygna viduata*	-	-	Moderate	-	-
Yellow-billed duck	*Anas undulata*	-	-	Moderate	-	-
Grey-headed gull	*Chroicocephalus cirrocephalus*	-	-	Moderate	-	-
Hamerkop	*Scopus umbretta*	-	-	Moderate	-	-
African grey hornbill	*Tockus nasutus*	-	-	Moderate	-	-
African sacred ibis	*Threskionis aethiopicus*	-	-	Moderate	-	-
Glossy ibis	*Plegadis falcinellus*	-	-	Moderate	-	-

Hadeda ibis	*Bostrychia hagedash*	-	-	Moderate	-	-
Greater painted-snipe	*Rostratula benghalensis*	-	-	Moderate	-	-
Southern pochard	*Netta erythrophthalma*	-	-	Moderate	-	-
African spoonbill	*Platalea alba*	-	-	Moderate	-	-
Cape teal	*Anas capensis*	-	-	Moderate	-	-
Red-billed teal	*Anas erythrorhyncha*	-	-	Moderate	-	-
Common ostrich	*Struthio camelus*	-	-	-	-	High
Crested barbet	*Trachyphonus vaillantii*	-	-	-	-	Moderate
Southern red bishop	*Euplectes orix*	-	-	-	-	Moderate
Brubru	*Nilaus afer*	-	-	-	-	Moderate
Cinnamon-breasted bunting	*Emberiza tahapisi*	-	-	-	-	Moderate
Golden-breasted bunting	*Emberiza flaviventris*	-	-	-	-	Moderate
Black-throated canary	*Crithagra atrogularis*	-	-	-	-	Moderate
Familiar chat	*Cercomela familiaris*	-	-	-	-	Moderate
Desert cisticola	*Cisticola aridulus*	-	-	-	-	Moderate
Levaillant's cisticola	*Cisticola tinniens*	-	-	-	-	Moderate
Zitting cisticola	*Cisticola juncidis*	-	-	-	-	Moderate
Long-billed crombec	*Sylvietta rufescens*	-	-	-	-	Moderate
Cape crow	*Corvus capensis*	-	-	-	-	Moderate
Pied crow	*Corvus albus*	-	-	-	-	Moderate
Diderick cuckoo	*Chrysococcyx caprius*	-	-	-	-	Moderate
Laughing dove	*Spilopelia senegalensis*	-	-	-	-	Moderate
Namaqua dove	*Oena capensis*	-	-	-	-	Moderate
Red-eyed dove	*Streptopelia semitorquata*	-	-	-	-	Moderate
Rock dove	*Columba livia*	-	-	-	-	Moderate
Booted eagle	*Hieraaetus pennatus*	-	-	-	-	Moderate
Yellow-bellied eremomela	*Eremomela icteropygialis*	-	-	-	-	Moderate
Common fiscal	*Lanius collaris*	-	-	-	-	Moderate

Spotted flycatcher	*Muscicapa striata*	-	-	-	-	Moderate
Gabar goshawk	*Micronisus gabar*	-	-	-	-	Moderate
African hoopoe	*Upupa africana*	-	-	-	-	Moderate
Greater kestrel	*Falco rupicoloides*	-	-	-	-	Moderate
Rock kestrel	*Falco rupicolus*	-	-	-	-	Moderate
Black-shouldered kite	*Elanus axillaris*	-	-	-	-	Moderate
Red-capped lark	*Calandrella cinerea*	-	-	-	-	Moderate
Sabota lark	*Calendulauda sabota*	-	-	-	-	Moderate
Spike-heeled lark	*Chersomanes albofasciata*	-	-	-	-	Moderate
Banded martin	*Riparia cincta*	-	-	-	-	Moderate
Brown-throated martin	*Riparia paludicola*	-	-	-	-	Moderate
Rock martin	*Ptyonoprogne fuligula*	-	-	-	-	Moderate
Southern masked-weaver	*Ploceus velatus*	-	-	-	-	Moderate
Red-faced mousebird	*Urocolius indicus*	-	-	-	-	Moderate
Neddicky	*Cisticola fulvicapilla*	-	-	-	-	Moderate
European nightjar	*Caprimulgus europaeus*	-	-	-	-	Moderate
Rufous-cheeked nightjar	*Caprimulgus rufigena*	-	-	-	-	Moderate
Speckled pigeon	*Columba guinea*	-	-	-	-	Moderate
African pipit	*Anthus cinnamomeus*	-	-	-	-	Moderate
Buffy pipit	*Anthus vaalensis*	-	-	-	-	Moderate
Black-chested prinia	*Prinia flavicans*	-	-	-	-	Moderate
African quailfinch	*Ortygospiza atricollis*	-	-	-	-	Moderate
Red-billed quelea	*Quelea quelea*	-	-	-	-	Moderate
Cape robin-chat	*Cossypha caffra*	-	-	-	-	Moderate
Purple roller	*Coracias naevius*	-	-	-	-	Moderate
Crimson-breasted shrike	*Laniarius atrococcineus*	-	-	-	-	Moderate
Lesser grey shrike	*Lanius minor*	-	-	-	-	Moderate
Red-backed shrike	*Lanius collurio*	-	-	-	-	Moderate

House sparrow	*Passer domesticus*	-	-	-	-	Moderate
Southern grey-headed sparrow	*Passer diffusus*	-	-	-	-	Moderate
White-browed sparrow-weaver	*Plocepasser mahali*	-	-	-	-	Moderate
Cape glossy starling	*Lamprotornis nitens*	-	-	-	-	Moderate
Wattled starling	*Creatophora cinerea*	-	-	-	-	Moderate
African stonechat	*Saxicola torquatus*	-	-	-	-	Moderate
Marico sunbird	*Cinnyris mariquensis*	-	-	-	-	Moderate
Barn swallow	*Hirundo rustica*	-	-	-	-	Moderate
Greater striped swallow	*Hirundo cucullata*	-	-	-	-	Moderate
White-throated Swallow	*Hirundo albigularis*	-	-	-	-	Moderate
Brown-crowned tchagra	*Tchagra australis*	-	-	-	-	Moderate
Groundscraper thrush	*Psophocichla litsitsirupa*	-	-	-	-	Moderate
Cape turtle-dove	*Streptopelia capicola*	-	-	-	-	Moderate
Cape wagtail	*Motacilla capensis*	-	-	-	-	Moderate
Willow warbler	*Phylloscopus trochilus*	-	-	-	-	Moderate
Common waxbill	*Estrilda astrild*	-	-	-	-	Moderate
Capped wheatear	*Oenanthe pileata*	-	-	-	-	Moderate
Pin-tailed whydah	*Vidua macroura*	-	-	-	-	Moderate
Pied avocet	*Recurvirostra avosetta*	-	-	-	-	-
European bee-eater	*Merops apiaster*	-	-	-	-	-
Red-knobbed coot	*Fulica cristata*	-	-	-	-	-
Reed cormorant	*Microcarbo africanus*	-	-	-	-	-
Double-banded courser	*Rhinoptilus africanus*	-	-	-	-	-
African darter	*Anhinga rufa*	-	-	-	-	-
Cattle egret	*Bubulcus ibis*	-	-	-	-	-
Great egret	*Ardea alba*	-	-	-	-	-
Little egret	*Egretta garzetta*	-	-	-	-	-
Yellow-billed egret	*Egretta intermedia*	-	-	-	-	-

Black-necked grebe	*Podiceps nigricollis*	-	-	-	-	-
Great crested grebe	*Podiceps cristatus*	-	-	-	-	-
Little grebe	*Tachybaptus ruficollis*	-	-	-	-	-
Common greenshank	*Tringa nebularia*	-	-	-	-	-
Blacksmith lapwing	*Vanellus armatus*	-	-	-	-	-
Crowned lapwing	*Vanellus coronatus*	-	-	-	-	-
Common moorhen	*Gallinula chloropus*	-	-	-	-	-
Kittlitz's plover	*Charadrius pecuarius*	-	-	-	-	-
Three-banded plover	*Charadrius tricollaris*	-	-	-	-	-
Ruff	*Philomachus pugnax*	-	-	-	-	-
Marsh sandpiper	*Tringa stagnatilis*	-	-	-	-	-
Black-winged stilt	*Himantopus himantopus*	-	-	-	-	-
Little stint	*Calidris minuta*	-	-	-	-	-
Alpine swift	*Tachymarptis melba*	-	-	-	-	-
Common swift	*Apus apus*	-	-	-	-	-
Little swift	*Apus affinis*	-	-	-	-	-
White-rumped swift	*Apus caffer*	-	-	-	-	-
Whiskered tern	*Chlidonias hybrida*	-	-	-	-	-
White-winged tern	*Chlidonias leucopterus*	-	-	-	-	-
Spotted Thick-knee	*Burhinus capensis*	-	-	-	-	-

Appendix B: List of bird species used in the searcher efficiency and carcass persistence trials at the Jasper PV solar facility in the Northern Cape, South Africa.

Searcher efficiency trials			
Size class	Common name	Scientific name	Number
Small (<100 g)	Fawn-coloured lark	*Calendulauda africanoides*	3
	Namaqua dove	*Oena capensis*	5
	Lark-like bunting	*Emberiza impetuani*	2
	Southern red bishop[1]	*Euplectes orix*	4
	White-browed sparrow-weaver	*Plocepasser mahali*	1
	Yellow canary[2]	*Crithagra flaviventris*	1
Medium (100-1000 g)	Blacksmith lapwing	*Vanellus armatus*	2
	Crowned lapwing	*Vanellus coronatus*	1
	Feral pigeon	*Columba livia domestica*	3
	Green pigeon	*Treron calvus*	4
Large (>1000 g)	Hadeda ibis	*Bostrychia hagedash*	4
		Total	30

Carcass persistence trials			
Size class	Common name	Scientific name	Number
Small (<100 g)	Common quail	*Coturnix coturnix*	12
	Fawn-coloured lark	*Calendulauda africanoides*	3
	House sparrow	*Passer domesticus*	5
	Namaqua dove	*Oena capensis*	5
	Southern red bishop[1]	*Afrotis afraoides*	4
	Yellow canary[2]	*Crithagra flaviventris*	1
Medium (100-1000 g)	Blacksmith lapwing	*Vanellus armatus*	2
	Crowned lapwing	*Vanellus coronatus*	1
	Feral pigeon	*Columba livia domestica*	2
	Green pigeon	*Treron calvus*	5
Large (>1000 g)	Hadeda ibis	*Bostrychia hagedash*	5
		Total	45

[1] Southern red bishop: one colourful male and 3 females/ plain males
[2] Yellow canary: one colourful male

Appendix C: Comprehensive list of bird species observed within and around the Jasper PV solar facility in the Northern Cape, South Africa. Bird species are defined based on their preferred habitat (Hockey et al. 2005).

Common name	Scientific name	Preferred habitat: Open grassland	Shrubland	Woodland[1]	Rocky outcrops	Open water bodies	Man-made habitats[2]
Cape penduline-tit	*Anthoscopus minutus*		×				
African red-eyed bulbul	*Pycnonotus nigricans*		×			×	
European bee-eater	*Merops apiaster*		×				×
Kalahari scrub-robin	*Cercotrichas paena*		×				×
Red-billed quelea	*Quelea quelea*		×				×
Namaqua dove	*Oena capensis*		×				×
Cape bunting	*Emberiza capensis*		×		×		×
Rock martin	*Ptyonoprogne fuligula*				×		×
White-backed mousebird	*Colius colius*			×		×	×
Familiar chat	*Cercomela familiaris*			×	×		×
Southern pale chanting goshawk	*Melierax canorus*			×	×		
Fawn-coloured lark	*Calendulauda africanoides*		×	×			
Grey-backed cisticola	*Cisticola subruficapilla*		×	×			
Violet-eared waxbill	*Uraeginthus granatinus*		×	×			
Red-backed shrike	*Lanius collurio*		×	×			
Karoo scrub-robin	*Cercotrichas coryphoeus*		×	×			
Red-crested korhaan	*Lophotis ruficrista*		×	×			
Chestnut-vented tit-babbler	*Parisoma subcaeruleum*		×	×			
Black-chested prinia	*Prinia flavicans*		×	×			×
Neddicky	*Cisticola fulvicapilla*		×	×			×
Yellow-bellied eremomela	*Eremomela icteropygialis*		×	×			×
Pied crow	*Corvus albus*		×	×			×
Scaly-feathered finch	*Sporopipes squamifrons*		×	×			×

Black-throated canary	*Crithagra atrogularis*		×	×			×
Yellow canary	*Crithagra flaviventris*		×	×			×
Bokmakierie	*Telophorus zeylonus*		×	×			×
Buffy pipit	*Anthus vaalensis*	×					×
Northern black korhaan	*Afrotis afraoides*	×					×
Black-headed heron	*Ardea melanocephala*	×				×	
Cape wagtail	*Motacilla capensis*	×				×	×
Southern red bishop	*Euplectes orix*	×				×	×
Eastern Clapper Lark	*Mirafra fasciolata*	×	×				
Spike-heeled Lark	*Chersomanes albofasciata*	×	×				
Spur-winged goose	*Plectropterus gambensis*	×	×			×	×
Spotted thick-knee	*Burhinus capensis*	×	×			×	×
Desert cisticola	*Cisticola aridulus*	×	×				
Greater-striped swallow	*Hirundo cucullata*	×	×				×
Plain-backed pipit	*Anthus leucophrys*	×	×				×
Ant-eating chat	*Myrmecocichla formicivora*	×	×				
Helmeted guineafowl	*Numida meleagris*	×	×				
House sparrow	*Passer domesticus*	×	×				×
Orange River francolin	*Scleroptila levaillantoides*	×	×				
Namaqua sandgrouse	*Pterocles namaqua*	×	×				
Rock kestrel	*Falco rupicolus*	×	×		×		×
Alpine swift	*Tachymarptis melba*	×	×	×	×		
Little swift	*Apus affinis*	×	×	×	×		×
White-rumped swift	*Apus caffer*	×	×	×			
Crowned lapwing	*Vanellus coronatus*	×	×	×			×
Laughing dove	*Streptopelia senegalensis*	×	×	×			×
Cape turtle dove	*Streptopelia capicola*	×	×	×			×
Burchell's Courser	*Cursorius rufus*	×	×	×			×
Chat flycatcher	*Bradornis infuscatus*	×	×	×			
Fiscal flycatcher	*Sigelus silens*	×	×	×			

Cape sparrow	*Passer melanurus*	×	×	×			×
Common fiscal	*Lanius collaris*	×	×	×			×
Barn swallow	*Hirundo rustica*	×	×	×		×	×

[1] Open to dense woodland (including drainage lines)
[2] Urban areas, gardens, parks, golf courses, and croplands

Appendix D: List of fatal and non-fatal detections of bird species recorded during the avian mortality surveys at the Japer PV solar facility in the Northern Cape, South Africa.

Date	Common name	Scientific name	Survey type[1]	Location	Condition of bird/carcass[2]	Suspected cause	Level of certainty[3]
14/09/2015	Fiscal flycatcher	*Sigelus silens*	Clearance	Under solar panel	Feather spot	Unknown	NA
15/09/2015	African red-eyed bulbul	*Pycnonotus nigricans*	Clearance	Perimeter fence	Carcass	Unknown	NA
15/09/2015	Orange river francolin	*Scleroptila levaillantoides*	Clearance	Under solar panel	Feather spot	Unknown	NA
22/09/2015	Orange river francolin	*Scleroptila levaillantoides*	Systematic	Under solar panel	Feather spot	Unknown	NA
24/09/2015	Fiscal flycatcher	*Sigelus silens*	Systematic	Under solar panel	Feather spot	Unknown	NA
25/09/2015	Orange river francolin	*Scleroptila levaillantoides*	Systematic	Under solar panel	Feather spot	Unknown	NA
19/10/2016	Eastern clapper lark	*Mirafra apiata*	Systematic	Under solar panel	Feather spot	Unknown	NA
02/11/2015	Speckled pigeon	*Columba guinea*	Systematic	Under solar panel	Feather spot	Unknown	NA
26/11/2015	Fiscal flycatcher	*Sigelus silens*	Systematic	Under solar panel	Feather spot	Unknown	NA
28/11/2015	Orange river francolin	*Scleroptila levaillantoides*	Systematic	Under solar panel	Feather spot	Unknown	NA
14/09/2015	Orange river francolin	*Scleroptila levaillantoides*	Systematic	Under solar panel	Uninjured	Non-fatal collision	Observed
14/09/2015	Orange river francolin	*Scleroptila levaillantoides*	Systematic	Under solar panel	Uninjured	Non-fatal collision	Observed
14/10/2015	Orange river francolin	*Scleroptila levaillantoides*	Systematic	Under solar panel	Uninjured	Non-fatal collision	Observed
14/10/2015	Orange river francolin	*Scleroptila levaillantoides*	Systematic	Under solar panel	Uninjured	Non-fatal collision	Observed
02/10/2015	Orange river francolin	*Scleroptila levaillantoides*	Systematic	Perimeter fence	Feather spot	Entrapment	Valid
09/10/2015	Red-crested korhaan	*Lophotis ruficrista*	Systematic	Perimeter fence	Uninjured	Entrapment	Observed
12/11/2015	Red-crested korhaan	*Lophotis ruficrista*	Systematic	Perimeter fence	Uninjured	Entrapment	Observed
30/11/2015	Red-crested korhaan	*Lophotis ruficrista*	Systematic	Perimeter fence	Uninjured	Entrapment	Observed

14/10/2015	Crowned lapwing	*Vanellus coronatus*	Incidental	Main road	Carcass	Vehicle strike	Valid

[1] Clearance - avian fatalities detected and removed from the study site prior to the scheduled surveys that will not be included in the fatality estimates, systematic surveys - avian fatalities detected that will be included in the fatality estimates, incidental - avian fatalities detected outside the scheduled surveys that will not be included in the fatality estimates.

[2] African red-eyed bulbul: fresh (within a week old, with soft flesh remains and fresh feathers); crowned lapwing: recent (within two months old, with dried flesh remains and numerous feathers still present); other: > 10 feathers of any type concentrated in an area less than 3 m^2

[3] Observed - 100%, valid - >90% certainty; probable - >50% certainty; possible - <50%, but > 0% certainty; not applicable - 0% certainty or unknown