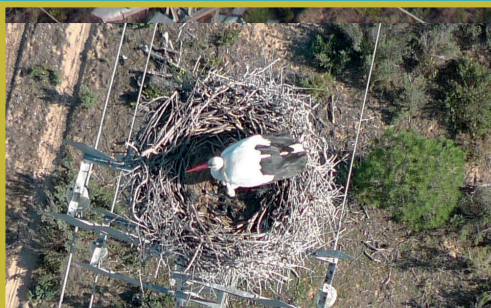
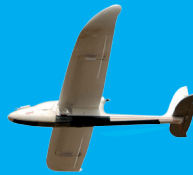


Unmanned Aerial Systems in Conservation Biology

Ph.D. Thesis

Margarita Mulero Pázmány
2015



**Utilización de sistemas aéreos no tripulados
en biología de la conservación**

Tesis doctoral



Unmanned Aerial Systems in Conservation Biology

Utilización de sistemas aéreos no tripulados en biología de la conservación

Ph.D. thesis / Tesis doctoral

Margarita Mulero Pázmány

Supervisor

Dr. Juan José Negro Balmaseda

Doñana Biological Station (DBS-CSIC)

Tutor

Dr. Carlos Antonio Granado Lorenzo

University of Seville

University of Seville. 2015

Dedicated to my family

Contents

• List of acronyms	2
• Abstract.....	3
• General introduction	5
• Aims	17
• Structure	19
• Chapter 1: Environmental impact assessment of infrastructures. A low cost way for assessing bird risk hazards in power lines: Fixed-wing small unmanned aircraft systems.	21
• Chapter 2: Management of endangered species. Remotely Piloted Aircraft Systems as a Rhinoceros Anti-Poaching Tool in Africa.	37
• Chapter 3: Conservation in a human dominated landscape. The eye in the sky: combined used of unmanned aerial systems and GPS data-loggers for ecological research and conservation of small birds.	63
• Chapter 4: Conservation in a protected area. Could Unmanned Aerial Systems constitute an alternative to bio-logging for animal spatial ecology studies?	83
• General discussion	103
• Conclusions.....	109
• Literature cited.....	111
• Acknowledgements.....	129
• Agradecimientos.....	133

List of acronyms

AESA	Agencia Estatal de Seguridad Aérea
AGL	Above Ground Level
BLOS	Beyond Line Of Sight
EASA	European Aviation Safety Agency
EDA	European Defense Agency
FAA	Federal Aviation Administration
HALE	High Altitude Long Endurance
ICAO	International Civil Aviation Organization
INTA	Instituto Nacional de Técnica Aeroespacial
JAA	Joint Aviation Authorities
JAPCC	Joint Air Power Competence Center
LOS	Line Of Sight
MALE	Medium Altitude Long Endurance
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NOAA	National Oceanic and Atmospheric Administration
RGB	Red-Green-Blue
RPAS	Remote Piloted Aerial (or Aircraft) Systems
SACAA	South African Civil Aviation Authority
SAMAA	South African Model Aircraft Associaton
STANAG	Standardization Agreement
UAS	Unmanned Aerial (or Aircraft) Systems
UAV's	Unmanned Aerial Vehicles

Abstract

Unmanned Aerial Systems (UAS) have been used for decades in the military field, mainly in dangerous or tedious missions where it is preferable to send a vehicle equipped with sensors than to use human piloted conventional aircrafts for information gathering.

In recent years technology has advanced, the market has grown exponentially, prices have descended and the use of the systems is simpler, which has led to the incorporation of the UAS to the civilian world. UAS have proven useful in ecology related tasks, such as animals monitoring and habitats characterization, and their potential for spatial ecology has been pointed out, but to date there are just a few studies addressing their specific use in conservation biology.

This Ph.D. thesis attempts to fill the gap of knowledge in practical functions of small UAS in conservation biology. It describes for the first time the use of these systems in an immediately applicable way for impact assessment of infrastructures and protection of endangered species. It also presents UAS as a tool for obtaining high-resolution spatiotemporal information, which helps to understand habitat use in rapidly changing landscapes. Furthermore, it demonstrates that these systems can provide information as valid as the obtained by conventional techniques on the spatial distribution of species in protected areas.

The experiments performed in the frame of this thesis show that low cost small UAS equipped with embarked cameras that provide high-resolution images offer the possibility of monitoring the environment at the researcher's desired frequency and revisiting sites to perform systematic studies, which is valuable for ecological research.

The results also revealed that UAS use in conservation biology has some constraints, mainly related with the scope of the missions, the limiting costs of the systems, operating restrictions associated to weather, legal limitations and the need of specialized personnel for operating the systems, as well as some difficulties for data analysis related with image processing.

Overall, given the novelty of the subject and the importance it is expected to have in the near future, I consider that providing information on the capabilities and

limitations of UAS, based on practical experiments in conservation biology, is not only of scientific interest but combines environmental and industry interests, which brings added value and usefulness of this thesis to society.

“The unmanned vehicle today is a technology akin to the importance of radars and computers in 1935”. Dr. Edward Teller

General Introduction

What are UAS?

There is a considerable controversy over the definition and the terminology for Unmanned Aerial Systems, mostly referred by UAS, an acronym that in fact is also valid for Unmanned Aircraft Systems. As the use of this equipment is the main core of the thesis, I will briefly describe the fundamental concepts. In addition to the academic need to clearly define the work subject, the use of different terms is quite relevant in this topic, as it affects the inclusion of the systems in categories subjected to operating conditions by the legal frame.

An aircraft is “a machine capable of flight” and unmanned means “needing no crew” (Oxford University Press 2014). Therefore, an unmanned aircraft could be defined as “a machine capable of flight needing no crew”. Traditionally, they were called Unmanned Aerial Vehicles (UAV's) (US Department of Defense 2014) but that literally refers only to the flying devices. In practice, to safely operate a UAV it is necessary to use support equipment (control station, ground personnel, communication and navigation systems), so considering that both the unmanned vehicle and the additional equipment form a system “set of things working together as parts of a mechanism or an interconnecting network” (Oxford University Press 2014), the industry and the regulators adopted Unmanned Aerial Systems (UAS) as the preferred term (FAA USA 2014). Please note there are some exceptions: “small model aircraft used for sport and cruise and ballistic missiles are not considered to be UAS” (Arjomandi 2007; UK Ministry of Defence 2010).

A few years ago the general media and the public showed some fright about the term “unmanned”, that led to the misunderstanding that there was no person in charge of the plane that could avoid a disaster in case of failure in flight (UK Ministry of Defence 2010). Because of that, the terms Remotely Piloted Aircraft (RPA), Vehicle (RPV) and Remote Piloted Aircraft (or Aerial) Systems (RPAS) (the latest including the whole system and not just the aircraft) started to gain importance in the legal context and to substitute UAS. Currently, the International Civil Aviation

Organization (ICAO), defines a Remotely-Piloted Aircraft System as “a set of configurable elements consisting of a remotely-piloted aircraft, its associated remote pilot station(s), the required command and control links and any other system elements as may be required, at any point during flight operation” (ICAO 2011). Considering that ICAO is a reference institution in the aeronautics field, this is probably the best term to name these systems and the most accepted definition.

Simultaneously to the experts’ debate and the hard work of the authorities to get a consensus on the terminology, generalist media started to use the term *drones*, first to refer to “UAS used in military applications”, but then by extension to refer to any UAS, which is not conceptually correct. This has created another debate with the majority of experts defending that *drones* should be reserved for military UAS, that the civil ones should be named simply UAS or RPAS and stating that the use of the word *drones* gives a bad image of civil UAS, while journalists prefer the term *drones* because the general public is familiarized with it. To complicate (or simplify) even more the polemic, some scientists and industry agents just decided to use the word *drones* and “stop wasting energy on this debate” see (Chapman, 2014) for further information on the current discussion.

In this thesis I preferably used the term Unmanned Aerial System (or the acronym UAS) because: 1) its definition is in accordance with the equipment that was used in most of the experiments; 2) it is the most widely used in the scientific literature; and 3) it is the most conservative term used in specialized conferences. In chapter 2, we used the term Remote Piloted Aircraft Systems because although the system we used had autonomous capabilities, all the flights were performed with real-time pilot’s control of the aircraft and therefore remotely piloted.

*Other terms that may be found to refer to UAS are: Flying robots, Remotely Operated Aircraft(s), Unmanned Aerospace Vehicle(s), Uninhabited Aircraft Vehicle, Unmanned Air Vehicle, Unmanned Airborne Vehicle, Unmanned Autonomous Vehicle, Unmanned Vehicle, Upper Atmosphere Vehicle

UAS origin and evolution

The first advances regarding UAS development are attributed to Nikola Tesla, who was granted a patent related to controlling mechanism of vehicles (Tesla 1898) and described a fleet of unmanned aerial combat vehicles in 1915 (U.S. Army 2010). Around World War I, United States produced the first UAS battle prototypes such as the first self-flying aerial torpedo, and although their performances were

criticized as unreliable and inaccurate, UAS military potential was recognized (Valavanis 2008). During World War II UAS were mainly used as radio-controlled targets and for reconnaissance missions (Finn & Wright 2012) but Germany developed an effective UAS that was used in combat as a weapon (NOVA 2002).

From their early use as target drones and remotely piloted combat vehicles, UAS acquired the new role of stealth surveillance during the Vietnam War (NOVA 2002). The modern UAS era originated in the early 1970s, when United States and Israel started experimenting with small UAS equipped with new video cameras that could send images to the operator in real time (Cox *et al.* 2004). In 1982 UAS demonstrated their critical importance on the Lebanon War, where they contributed decisively to Israel victory over Syrian's Air Forces. Along the 1980s and 90s United States, Israel and Europe research and development focused into further military uses of UAS, and since the first Gulf War, these systems are deployed in the majority of the armed conflicts (Kosovo 1999, Afghanistan since 2001 and Iraq since 2003). Some of the most famous UAS are: 1) Predator, that has performed surveillance and armed reconnaissance in the Balkans conflict and other later ones; 2) the evolved Reaper, armed with high precision missiles; and 3) Global Hawk, which has demonstrated its capacities in several operations in Iraq and Afghanistan (Lovelace (Jr.) & Boon 2014).

The estimations indicate that UAS will be the most dynamic growth sector of the world aerospace industry, particularly because of developments in lightweight construction materials, microelectronics, signal processing equipment, GPS navigation and payload sensors. Market studies from 2014 estimate that UAS spending will nearly double over the next decade from current worldwide UAS expenditures of \$6.4 billion annually to \$11.5 billion, totaling almost \$91 billion in the next ten years (Teal Group 2014).

As described above, the development of UAS has been mainly associated to military applications, but in the last ten years, an interesting technological convergence has taken place. On one hand, military UAS manufacturers started to produce smaller and more affordable products, designed for short-range military missions and easier to transfer to the civil market. On the other hand, radio-controlled model planes enthusiasts began to incorporate advances into their systems, using radio frequency amplifiers and embarking small video cameras, stabilizing systems, GPS and autopilots which have notoriously improved their performances (such as enabling to fly out of line of sight), all this favored by: open source software; an emergence of numerous forums where fans share knowledge; and the success of websites specialized in low cost electronic products and cameras (i.e. <http://diydrones.com/>,

<http://www.hobbyking.com>). These “amateur born” advances have finally led to a small but expanding industry specialized in small-scale systems and mainly focused on aerial photography where it is possible to find UAS at prices of lower magnitude orders than their closest counterparts in the traditional industry.

Teal Group last market study estimates the current UAS market at 89% military and 11% civil cumulative for the decade, with the numbers increasing to 14% civil by the end of the next 10-year, which reflects the rapid growth of interest in the UAS business, by covering more than 40 U.S., European, South African and Israeli companies (Teal Group 2014). These estimations are based not only in the widespread use in military tasks, but also on the assumption that regulations (Airworthiness, Certification) for the insertion of UAS in the open air space will be issued and will be achieved by the civil UAS operator companies.

UAS classification

There is an enormous variety of UAS in the market and they are used in very different applications, which makes it difficult to develop one classification that encompasses all the systems. The most conservative classification was stated by NATO, where UAS categories are based on the unmanned aircraft maximum gross, take-off weight and normal operating altitude. Categories start with weight classes and these weight classes are further divided on the basis of the operational altitude of the UAS (Table 1).

For other classifications based on different criteria such as weight, payload, endurance and range, speed, wing loading, engine type or mission nature see: Arjomandi, 2007; Cox et al., 2004 or UK Ministry of Defence, 2010.

Table 1: Unmanned Aircraft Classification. Extracted from (Joint Air Power Competence Centre, 2010)

Class	Category	Normal employment	Normal operating altitude	Normal mission radius	Primary supported commander	Example platform
CLASS I (less than 150 kg)	SMALL >20 kg	Tactical Unit (employs launch system)	Up to 5K ft. AGL	50 km (LOS)	BN/Regt, BG	Luna, Hermes 90
	MINI 2-20 kg	Tactical Sub-unit (manual launch)	Up to 3k ft. AGL	25 km (LOS)	Coy/Sqn	Scan Eagle, Skylark, Raven, DH3, Aladin, Strix
	MICRO <2 kg	Tactical Pl, Sect, Individual (single operator)	Up to 200 ft. AGL	5 km (LOS)	Pl, Sect	Black Widow
CLASS II (150 kg to 600 kg)	TACTICAL	Tactical Formation	Up to 10,000 ft. AGL	200 km (LOS)	Bde Comd	Sperwer, Iview 250, Hermes 450, Aerostar, Ranger
CLASS III (more than 600 kg)	Strike/Combat	Strategic/National	Up to 65,000 ft. AGL	Unlimited (BLOS)	Theatre COM	
	HALE	Strategic/National	Up to 65,000 ft. AGL	Unlimited (BLOS)	Theatre COM	Global Hawk
	MALE	Operational/Theatre	Up to 45,000 ft. AGL	Unlimited (BLOS)	JTF COM	Predator B, Predator A, Heron, Heron TP, Hermes 900

UAS flight regulations

The integration of UAS in airspace is a complex issue that has been addressed by a large number of national and international Civil Aviation organizations (Eurocontrol, JAA, EASA, FAA, ICAO) and Defense (i.e. NATO, EDA) assisted by research companies in the aviation sector and industry from a long time. The integration of these systems means to solve the problem of how technology can make UAS to be treated, for all purposes, as conventional aircrafts from the point of view of safety in the system and its operation. The answers will be obtained from studies on the required technologies (Communications and Data Link LOS and BLOS, Sense and Avoid Systems, Navigation and positioning, etc.) that are being conducted under the auspices of various organizations and through the analysis from different regulatory scenarios of control and airspace management and air traffic, accompanied by the issuance and acceptance of different specifications and standards. Currently

there is not a unique leader of initiatives on the integration of UAS, which produces a dispersion of efforts, but parallel studies are being developed according to the organism that promotes them (Dirección general de armamento y material. Ministerio de Defensa de España. 2008). To this, it must be added that in some aspects the United States and Europe follow separate processes in the methodology for addressing some of the integration issues, although in certain areas, specifications have been agreed as STANAG in NATO scope.

In Spain, AESA (Agencia Estatal de Seguridad Aérea) is the responsible of guaranteeing that the standards for civil aviation activity are met. In 2014 it approved a set of rules for aerial works with UAS, referred as drones (Jefatura del Estado 2014). The main topics contained in the new legal frame that can be considered relevant for UAS in conservation biology are resumed below:

1. Drones can be used for aerial works, such as research.
2. Drones can be used in uninhabited areas, but their use is not allowed in crowded areas or in segregated airspace. UAS flight is forbidden in a radio of 8 or 15 km (depending on drone mass) from airports.
3. Systems < 25 kg must be used in a 500 m range from the operator in line of sight, in daylight conditions and below 120 m AGL.
4. If drones are < 2 kg it is possible to operate them beyond line of sight under ground control station radio range, below 120m AGL and with a NOTAM from Aeronautical Information Services.
5. Drone pilots must be accredited with a pilot license or they have to demonstrate their capabilities with a certificate from and authorized agency by AESA or an approved training organization. Pilots must have a medical accreditation (Class APL or Class 2 depending on UAS mass). Finally, they must prove that they have adequate knowledge of the aircraft they use.
6. The operator or owner of the drone is required to have an appropriate insurance and detailed documentation that guarantees that the UAS operations are performed safely.
7. Drones must be identified with a plate containing the operator information.
8. Drones operators have to send AESA a communication of the flights and a responsible declaration stating that the drone complies with all the requirements at least 5 days before the flight is planned.

All the UAS experiments conducted in the frame of this thesis have been performed according to the normative and with the permits of the relevant authorities. The flights conducted in chapter 2 followed South African regulations (SACAA and SAMAA rules). The rest of the flights were performed in Spain before specific UAS regulations were developed. At that time, AESA could not approve UAS flights, but as the experiments were conducted in Doñana National Park classified as “LER Coto Doñana”, a polygon where “the over-flights, except state aircrafts and flights authorized for conservation by the Autonomous Organization of National Parks Park are forbidden” (Gobierno de España 2005), the permits from the National Park authorities and the communication of the flights to the local aerial control center was considered enough for the authorities to fly safely.

UAS missions and capabilities

UAS were originally developed to substitute manned aircrafts and avoid sending human pilots to perform tasks implying risk or fatigue. Therefore UAS missions have been traditionally classified as 3D missions: dull, dirty and dangerous. With such a variety in the market, from Class III UAS flying over 30 hours to micro UAS that fit in the palm of the hand, it is difficult to define a general pattern of their capabilities. In fact, the main feature that characterizes UAS as a whole is the possibility to create tailored systems, by choosing the aerial platform and the payload (onboard sensors), which gives the end user a high flexibility in the type of mission to perform. This allows not only substituting traditionally manned aircraft tasks but also the emergence of new lines of research in the field of military and civil applications.

Although “UAS applications are limited only by our imagination” (sentence attributed to Mike Heintz, UNITE Alliance, in Finn & Wright, 2012) the most realistic civil applications are listed below and can be further explored in Cox *et al.* (2004):

- Remote sensing
- Commercial aerial surveillance.
- Media industry: sports, filming companies.
- Oil gas and mineral exploitation and production.
- Disaster relief and medical assistance.
- Archaeology research.

- Homeland security: coastal patrol, domestic police missions, border surveillance, public protests monitoring, drug plantations detection.
- Environmental monitoring: wildlife census, animal tracking and invasive plants assessment.
- Land management: forest fire damage assessment, forest fire mapping, forest fire communications, retardants application.
- Agriculture: crops productivity assessment, crops spraying, vineyards monitoring (Berni *et al.* 2009).

UAS integration in environmental research

Given the advances in UAS technology and the growing diffusion by the media, it is not surprising that scientists started to explore the use of UAS for environmental monitoring. This process started about a decade ago and has evolved in two contexts differentiated by project budget and UAS access scenarios, which led to the current parallel existence of two lines of work at different scales.

1) Large scale projects: mainly conducted by NASA and NOAA using large and medium UAS with high range (>25 km), and autonomy (>4 hours) and capacity to carry payload formed by advanced sensors.

UAS (including payload) prices are generally over 100.000 € and require high operational costs. Some of the most popular systems are: Global Hawk, Manta, Scan Eagle, Altair, Aerosonde, Ikhana, SIERRA, R100 Marine and Aerocam.

Research topics (already conducted or planned) are mostly related with earth science: climate change, atmospheric research (meteorology and chemistry), large scale fire, vegetation structure, composition and canopy chemistry, glacier and ice sheet dynamics, surface deformation, imaging spectroscopy, topographic mapping, gravitational acceleration measurements, Antarctic and Arctic exploration surveys, magnetic fields measurements, river discharge, soil moisture and freeze, landfall and physical oceanography (Williamson 2011; NOAA 2014).

2) Local scale projects: generally conducted by university or research centers' departments and local UAS companies using small systems with short operational ranges (<25km) and autonomy (<4 hours). Payloads are basic, generally RGB still photo or video cameras and thermal sensors, and less frequently: meteorological

sensors, broadband or narrowband pyranometer-type radiometric sensors, or lightweight miniaturized hyperspectral radiometers (Anderson & Gaston 2013).

UAS (including payload) prices are generally below 100.000 € and operations are mostly performed by the members of the research group who get training in piloting. Small UAS are frequently fully or partially self-made or acquired in the amateur market, although there are also some new professional-commercial systems. Some of the most popular systems are: Gatewing x100, Quest UAV, SUMO, MMAV, BAT-3, CSIRO, Droidworx multicopter, Iris+, Aero, Draganflyer X4, Nova2, Fulmar, Cryowing, Mikrokopter, UAS developed by Conservation Drones, DIY and MLB Foldbat (more platforms with actual and possible uses in environmental research are reviewed in Anderson & Gaston, 2013).

Research topics are often a further extension of the subject the group was already studying by other means, with UAS contributing to get an aerial perspective. The main works that have been performed or are currently being conducted in this field (excluding the ones presented in this thesis) can be classified as:

- 1) Wildlife surveys: mainly focused on the evaluation of the systems for different species detection and their feasibility for a more generalized use (table 2).
- 2) Habitat characterization: mainly focused on vegetation and landscape characterization, although some of them present a more ecological approach (e.g. animals' habitat selection) (table 3).
- 3) Methodological studies: focused on advances in techniques for data processing or the specific design of systems for environmental purposes (Table 4).

Table 2: UAS wildlife surveys studies.

Animal group	Location	References
Birds		
Water birds	Florida, US	Jones 2003; Frederick et al. 2009; Watts et al. 2010
Black headed gulls	North East of Spain	Sardà-Palomera et al. 2012
Geese	Canada	Chabot and Bird 2012
Sandhill cranes	Colorado, US	Farrell 2013
Steller's sea eagle	Russia	Potapov <i>et al.</i> 2013
Gull colonies	Germany	Grenzdörffer 2013
Ospreys	Montana, US	Averett 2014
Terrestrial Mammals		
Roe deer	Germany	Israel 2011
Rhinoceros	South Africa	Dewar 2013; WcUAVC 2013
Rhinoceros	Zimbabwe	Olivares-Mendez and Bissyand 2013
Elephants	Democratic Republic of Congo	Linchant et al. 2013
Elephants	Mozambique	Mander 2013
Elephants	Burkina Faso	Vermeulen et al. 2013
Elephants	Kenya	Schiffman 2014
Rhinoceros and orangutans	Indonesia	Gemert et al. 2014
Marine mammals and fish		
Manatees and alligators	Florida, US	Jones 2003; Jones et al. 2006
Humpback whales and dugongs	Western Australia	Pyper 2008; Hodgson et al. 2013
Marine mammals	Washington, US	Koski et al. 2009
Chinook salmon	Oregon, Washington and Utah, US	AeryonLabs 2014

Table 3: UAS habitat characterization studies.

Subject	Location	References
Ecological research and natural-resource monitoring	Latin America	Watts et al. 2008
Characterization of Mediterranean riparian forest	Southern France	Dunford et al. 2009
Coastal research		Pereira et al. 2009
Rangeland monitoring	New Mexico	Laliberte et al. 2011
Assessing biodiversity in forests	Germany	Getzin et al. 2012
Survey and map in tropical forests	Indonesia	Koh and Wich 2012
Map fearscapes for pygmy rabbits	Russia	Olsoy et al. 2013
Wetlands monitoring	Canada	Chabot and Bird 2013; Chabot et al. 2014
River mapping	Not specified	Room and Ahmad 2014
Community-based forest monitoring	Malaysia, Nepal and Indonesia	Paneque-Gálvez et al. 2014
Marshlands monitoring	New South Wales, Australia	ABC 2014
Environmental monitoring of epidemiology	Malaysia and Philippines	Fornace et al. 2014

Table 4: UAS methodological studies

Method	References
Development of a UAV for wildlife surveillance	Lee 2004
Algorithm for automatic bird detection	Abd-elrahman et al. 2005
Geo-referencing techniques	Wilkinson 2007
Estimating distribution of hidden objects	Martin et al. 2012
Estimating the surface area of sampling strips	Lisein et al. 2013
Bio-logged wildlife tracking	Soriano et al. 2009; Körner et al. 2010; Leonardo et al. 2013
Remote water sampling	Schwarzbach et al. 2014
Reviews	
UAS in Remote Sensing	Watts et al. 2012
UAS for Spatial ecology	Anderson and Gaston 2013

Why UAS in conservation biology?

Conservation biology is a mission-oriented science that focuses on how to protect and restore biodiversity dealing with issues where quick action is critical. To effectively inform policy and management authorities, conservation research must address the most pressing problems and the most threatened systems and organisms (Soulé 2007; SCB 2014).

Despite the explosion of projects with UAS for environmental applications in the recent years, there is still a lack of studies that fit into the philosophy of conservation biology, i.e. providing solutions that are immediately applicable to solve urgent environmental problems. Doñana Biological Station-CSIC in collaboration with several institutions, among which the Faculty of Engineering of the University of Seville is noteworthy, has participated since 2005 in three consecutive multidisciplinary projects focusing on the development of systems and techniques for the application of UAS to conservation biology:

1) SADCON (Andalusian Government, Project for Excellence, 2005 / TEP-375). Distributed autonomous systems for environmental conservation.

2) AEROMAB (Andalusian Government, Project for Excellence, 2007, P07-RNM-03246). Aerospace technologies for biodiversity conservation.

3) PLANET (7th Framework Program, cooperation FP7-257649) Platform for the deployment and operation of heterogeneous networked cooperating objects.

This Ph.D. thesis feeds from these projects although it is mainly framed within AEROMAB, which had a more immediate orientation.

Aims

The overall objective of this thesis is to evaluate the use of UAS in conservation biology, mainly for animal conservation. For this purpose we analyzed the systems capabilities and limitations in four specific use cases that may serve as examples of practical applications that address relevant topics in conservation.

- 1) How can UAS contribute to environmental impact assessment of infrastructures?
- 2) How can UAS contribute to management of endangered species?
- 3) Conservation in a human dominated landscape: Can UAS constitute a useful tool for obtaining high-resolution spatiotemporal information on animals habitat use in highly dynamic landscapes?
- 4) Conservation in a protected area: Are UAS capable of providing information as valid as the obtained by conventional techniques on the spatial distribution of species?

Structure

In addition to the general introduction, this thesis contains four chapters that explore the stated questions examining four representative use cases. To accomplish the objectives, we conducted several field campaigns using low-cost small UAS along the last five years. The first three chapters correspond to published papers and the last one to a submitted manuscript.

CHAPTER 1: Environmental impact assessment of infrastructures

Accidents on power lines are one of the most important causes of man-induced mortality for raptors and soaring birds. In this chapter we describe the use of low cost small Unmanned Aircraft Systems (sUAS) equipped with onboard cameras for power line surveillance. We characterized four power lines, geo-referenced every pylon in selected portions and assessed their hazard for birds. We compare the effectiveness of two variants of the sUAS method for data acquisition and two ways of plane control.

CHAPTER 2: Management of endangered species

Rhinoceros poaching is an urgent conservation issue that requires immediate solutions. In this chapter, we describe the use of a small low cost RPAS equipped with three different types of cameras to test their ability to support rhinoceros anti-poaching tasks in the KwaZulu-Natal province of South Africa. We performed several flights in order to test the technical capabilities of the system to detect rhinoceros, to reveal simulated poachers and to do fence surveillance. We evaluated the influence of flight altitude, time and habitat type in the effectiveness of the system. Considering the most common modus operandi of poachers, we also analyzed the aspects that affect remotely piloted aircraft's integration in anti-poaching operations.

CHAPTER 3: Conservation in a human dominated landscape

In this chapter we describe the combined use of GPS data loggers and environmental information recorded by UAS to study habitat selection of a small bird species, the lesser kestrel *Falco naumanni*, living in a human dominated highly dynamic landscape. After downloading the spatio-temporal information from the kestrels, we programmed the UAS to fly and document with pictures the paths of those same birds shortly after their flight, extracting environmental information at quasi-real time

that we used to study the availability of different habitat types along the bird flight path.

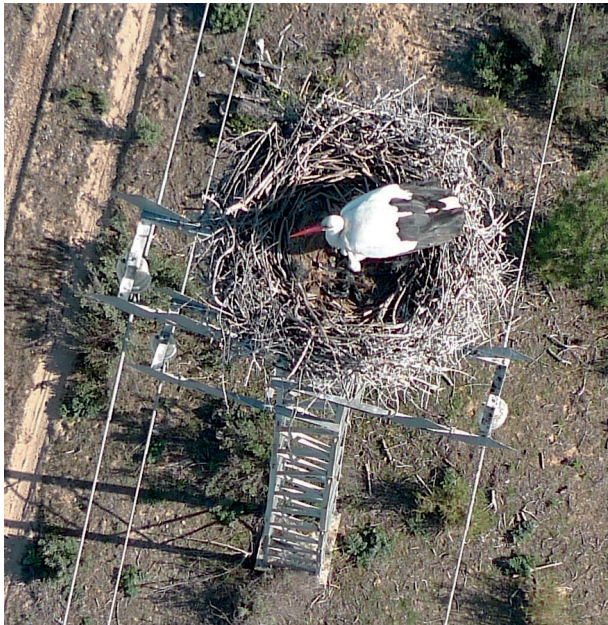
CHAPTER 4: Conservation in a protected area

In this chapter we assess the usefulness of UAS overflights to: i) get data to model the distribution of free-ranging cattle by comparing with results obtained from GPS-GSM collared cattle, and ii) predict species densities by comparing with actual density in Doñana Biological Reserve (South of Spain).

A general discussion analyzes UAS integration in conservation biology, considering the previous related studies and the four chapters together and the final conclusions provide a brief summary of the most relevant findings. The thesis concludes with a list of all the references cited along the text and acknowledgements to the people and institutions that have contributed to this work.

"Nobody realizes that there are some people who spend excessive energy just to look normal". Albert Camus

Chapter 1: Environmental impact assessment of infrastructures



[This Chapter is published as: Mulero-Pázmány, M., Negro, J. J., & Ferrer, M. (2014). A low cost way for assessing bird risk hazards in power lines: Fixed-wing small unmanned aircraft systems. *Journal of Unmanned Vehicle Systems*, 2(1), 5–15. doi:0.1139/juvs-2013-0012]

ABSTRACT

Accidents on power lines are one of the most important causes of man-induced mortality for raptors and soaring birds. The factors that condition the hazard have been extensively studied, and currently there are a variety of technical solutions available to mitigate the risk. Most of the resources in conservation projects to reduce avian mortality now are invested in fieldwork to monitor the lines, which diverts the resources available to install actual corrective measures to mitigate bird hazard. Little progress has been achieved in the methodology to characterize line risk, which is an expensive, tedious and time-consuming task. In this work we describe the use of low cost small Unmanned Aircraft Systems (sUAS) equipped with onboard cameras for power line surveillance. As a case study, we characterized four power lines, geo-referenced every pylon in selected portions and assessed their hazard for birds. We compare the effectiveness of two variants of the sUAS method for data acquisition and two ways of plane control. This work provides evidence of the usefulness of sUAS as a fast, inexpensive and practical tool in conservation biology, adding to their already known applications in wildlife monitoring the environmental impact assessment of infrastructures.

Keywords: *power lines, bird electrocution, environmental impact of infrastructures, Fixed-wing sUAS, remotely piloted aircraft, drones.*

INTRODUCTION

Bird mortality on power lines is an important conservation issue recognized decades ago (Olendorff *et al.* 1981; Crivelli *et al.* 1988; Ferrer *et al.* 1991). Raptor and large bird species are especially prone to electrocution, mostly on distribution lines (Negro & Ferrer 1995), and collision with cables is more frequent on transmission lines, affecting gregarious species or birds that fly at times with reduced visibility (Negro 1987; Ferrer & Negro 1992; Ferrer & Janss 1999). The distribution of bird accidents on power lines has a significant tendency to accumulate on certain pylons or spans (cable length between two pylons) (Ferrer & Hiraldo 1991; CLAVE S.L. 1992). Thus, effectively correcting a small fraction of all pylons and/or spans of a given line it is possible to reduce total mortality drastically (Ferrer & Hiraldo 1991; López-López *et al.* 2011). Bird nesting on pylons is another situation that may increase electrocution risk and also produces damage to the infrastructures; both result in economic losses and reduce service quality for utility companies (Red Eléctrica 2005; Ferrer 2012).

Currently, the bulk of the effort in terms of time and costs to mitigate the bird hazard of power lines is invested in the fieldwork for the characterization phase of the study. Line monitoring is normally done by car or on foot (Katrashnik *et al.* 2008), identifying pylon design, recording pylon location with a GPS, identifying bird mortalities and surveying habitat types, all factors that would contribute to the assignment of risk values (Ferrer & Hiraldo 1991). There are other possibilities for power line study, such as using conventional aircraft with automatic video surveillance systems (Whitworth *et al.* 2001; Ma & Chen 2004), satellite images, rotary-wing unmanned aircraft systems (UAS) (Campoy *et al.* 2001; Peungsungwal *et al.* 2001; Ma & Chen 2004; Jones *et al.* 2005; Katrasnik *et al.* 2008; Li & Ruan 2010) and more sophisticated solutions, including climbing-flying robots (Katrašnik *et al.* 2008), but they are too expensive to be applied routinely in conservation biology studies or they have not been implemented realistically in the field yet.

Fixed-wing small Unmanned Aircraft Systems (sUAS) are undergoing remarkable development, which has led to a decrease in prices and a greater variety of equipment available. Their use has increased considerably for different purposes in military and civil applications. SUAS have been recently incorporated in wildlife conservation, mainly focusing on aerial wildlife surveys and habitat studies (Jones *et al.* 2006; Pereira *et al.* 2009; Watts *et al.* 2010; Chabot & Bird 2012; Rodríguez *et al.* 2012a; Sardà-Palomera *et al.* 2012; Getzin *et al.* 2012).

Here we describe the use of fixed-wing sUAS technology as a tool to characterize power lines to subsequently assess their impact on birds in a low cost way. We also compare the usefulness of two different types of cameras to identify and geo-reference power pylons and test as well two alternative variants of plane control.

MATERIAL AND METHODS

Study area

Fieldwork was conducted in two locations in southwestern Spain: an agricultural area in Dos Hermanas, Seville (5°56'16.1816''W, 37°15'22.462''N) and a preserved area within Doñana National Park, Huelva (6°31'58.8522''W, 37°6'53.2887''N). Surveys took place in March, April and December 2012.

SUAS technical specifications

We used the radio controlled Easy fly St-330 (St-models, China) propelled by a brushless electrical motor. Wingspan is 1.960 m and it has a Maximum Take-Off Weight (MTOW) of 2 kg with a 250 g payload (Figure 1). Its maximum range is 10 km, endurance 50 minutes and it can take off and land manually in small patches of flat and open terrain. Operations can be carried out in two different ways and it is possible to switch from one to the other during the flight.

-Automatic mode: the plane is controlled and guided by the autopilot system. No intervention from the pilot is required during the flight (only taking-off and landing are performed manually). The autopilot provides flight stabilization and the capability to program waypoints, and if the control signal is lost, the autopilot activates the “return home” mode.

-First Person View system (FPV): the pilot controls the plane in real time using virtual reality glasses and sees telemetry data superimposed on the video. The FPV system includes a long-range radio control receiver.

In both control modes, On-Screen Display (OSD) function provides real time flight information (course, altitude, speed, waypoints and artificial horizon) superimposed on the video signal from a camera located on the plane's nose, which can be visualized on the ground control station. Thus, the operators always have real time information of the area overflown.

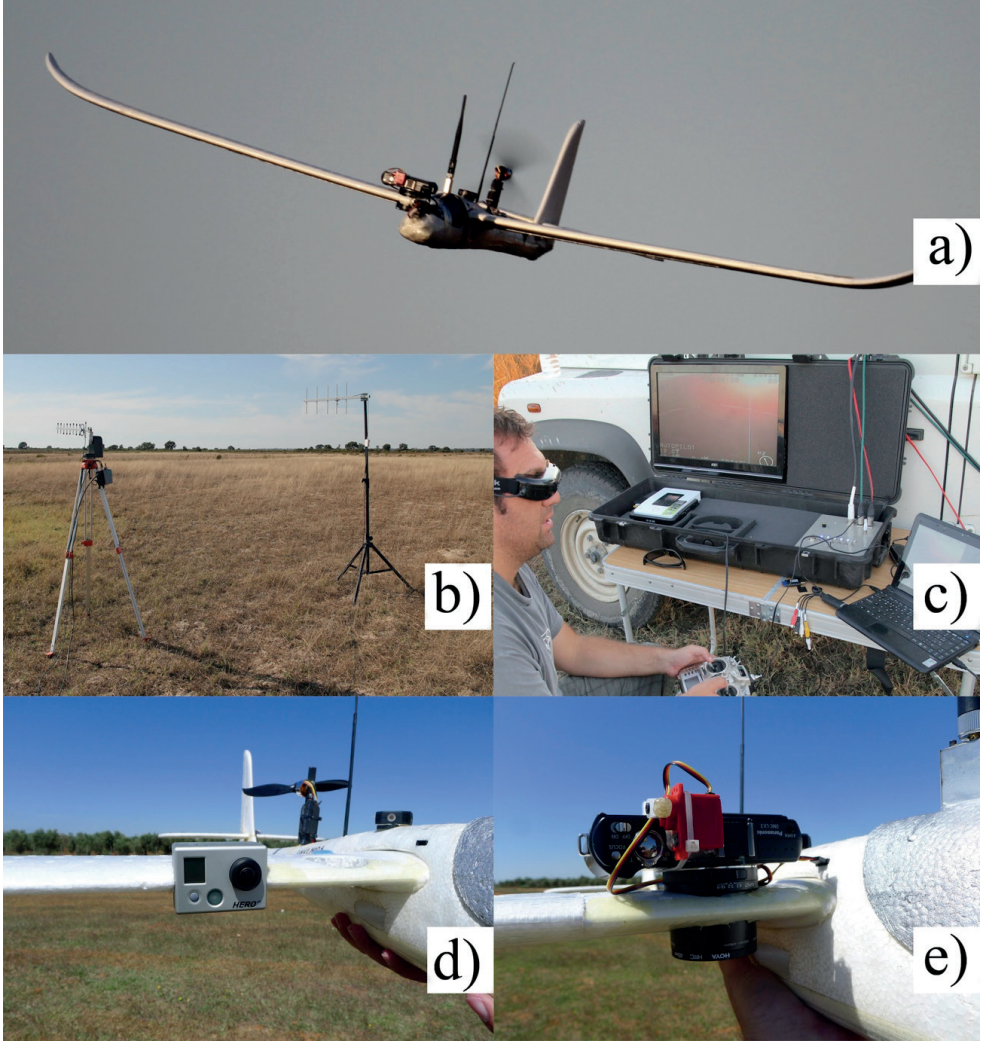
Payload

The sUAS is equipped with two different photo cameras (each one of them mounted on a different flight, but not concurrently): a Panasonic LX3, 11MP (Osaka, Japan) nadir pointing and a GoPro Hero 2, 11 MP (Woodman Labs., CA, USA) forward pointing, both programmed to take 1 picture/second. (Figure 1). We also included an Eagletree GPS, V.4 data logger (Eagletree systems, WA, USA), which provides accurate tracks of the plane (1 data/second) and includes a barometric altimeter that is used to geo-reference the pictures.

Ground control station

The ground station includes: a flight case, a video tracking system and a long-range radio control transmitter (Figure 1). The flight case contains the equipment needed to visualize the real time video from the plane: a TV monitor, virtual reality goggles, a DVD video recorder and a laptop that uses the data received with the video to track the UAS on a Microsoft (Redmond, WA, USA) map. The video tracking system integrates a high gain antenna, a motorized tracking system and a 1.2 GHz video receiver (Figure 1). Plane control signals are generated by a commercial radio control transmitter (WFT09, WFly, Shenzhen, China). The long range radio control system transmits this signal in the 434 MHz band using a high gain antenna. The signal emitted is digital and has a frequency hopping system that makes it very difficult to jam and the power output can be selected in the range of 0.5 W to 2 W. The approximate cost of the sUAS and its payload was 1,800 €, and the ground control station (including antennas) was about 6,000 €, as of June 2012.

Fig. 1. Description of our small unmanned aerial system: (a) aerial platform, (b) antennas, (c) ground control station, (d) wing-mounted forward-pointing camera, and (e) wing-mounted nadir-pointing camera.



Data gathering

We performed a total of thirteen flights at an altitude ranging from 20 to 50 m above ground level (AGL), at an average speed of 30 Km/h. Ten flights were done in FPV mode and the remaining three using the autopilot. Seven of the flights were performed with the ground-pointing camera and the remaining six with the front

pointing camera. We overflowed four power lines (one 60 kV transmission and three 15 kV distribution lines), photographing a total of 122 pylons and their respective spans.

The pylons were characterized and their hazard was evaluated using the criteria proposed by Clave (1992). We studied them independently by using images obtained from the ground as a control, from the forward pointing sUAS camera and from the nadir pointing UAS camera. Ground-truth data were obtained by walking along the lines recording the coordinates with a handheld GPS (Garmin Etrex Legend HCx) and photographing the pylons from their base.

Images obtained by the nadir-pointing camera had a horizontal view, so they could be superimposed on the map. Images were geo-referenced using a customized extension of ENVI software (Boulder, CO, USA) that synchronizes the track of the plane with image time stamps. It considered barometric altitude and course of the UAS, and generated a “.tiff” file that could be projected on a map. The coordinates of each pylon were obtained by marking its representation on the geo-referenced image. The forward mounted camera presented an oblique view, precluding superimposition on a map. The camera had a fisheye lens (a viewing angle of 165° horizontal and 160° vertical). When the top of the pylon appeared in the lower third of the picture, it was estimated that it was below the sUAS, so we considered the sUAS location at the exact time of the picture (registered in the time stamp of the file) to be the pylon location.

Using ground GPS data as a control, we measured the differences between the coordinates obtained with the sUAS flights using Microsoft Excel Version 14.3.1. To test the repeatability of each camera method we overflowed in FPV mode the same pylons twice with each camera method. The results of pylon locations in the four flights were compared under similar weather conditions. To check the differences between the two plane control methods (autopilot versus FPV) we compared the deviation from the power line trajectory in the two flights made per mode. The differences between the plane trajectories in relation to the programmed routes were calculated using the NEAR tool of Arc GIS 9.3 (ESRI, Redlands, CA, USA).

This study was conducted in accordance with EC Directive 86/609/EEC for animal handling and experiments, and with the current Spanish legislation involving aviation safety. Field technicians had the required licenses to operate in the frequencies used for this work. Doñana National Park authorities (Junta de Andalucía) approved permits to conduct this study.

RESULTS

A total of 17 different pylon designs were identified among the 122 pylons that we surveyed (Fig. 2, see also Fig 3 for examples obtained by the two airborne cameras, and Supplementary material 1 for a complete catalogue of all designs). Resolution of the images at 50 m AGL of the nadir pointing camera was 4.32 cm², and for the forward pointing camera was 8.72 cm². More than 50% of the pylons surveyed presented high electrocution hazard and 95% of the spans had a moderate collision risk for birds (see Table 1).

Table 1. Evaluation of the electrocution and collision hazard for birds of the pylons and spans surveyed.

Electrocution/ collision hazard	Number of pylons (%)	Number of spans (%)
Very low	6 (4.9%)	0 (0%)
Low	23 (18.9%)	6 (4.9%)
Moderate	14 (11.5%)	116 (95.1%)
High	63 (51.7%)	0 (0%)
Very high	16 (13.1%)	0 (0%)

Geo-referencing precision was significantly higher using the forward pointing camera ($mean = 18.01$ m, $sd = 12.00$ m, $n = 113$) compared to the nadir pointing camera ($mean = 22.11$ m, $sd = 11.15$ m, $n = 109$) (*Student's-t test for paired samples* = 3.70, $p < 0.05$) (Figure 4). In both cases, the mean error was lower than the inter-pylon distances (50 m for distribution lines and 100 m for transmission lines). In addition, as the observer knew the direction of the flights, it was not possible to confound one pylon with the adjacent one.

The repeatability of the forward-pointing camera ($mean = 11.1$ m, $sd = 8.2$, $n = 17$) was not significantly different (*Student's-t test for paired samples* = -0.10, $p = 0.92$) than the nadir-pointing camera method ($mean = 10.3$ m, $sd = 6.0$, $n = 14$).

There were significant differences (*Kruskal-Wallis test*, $H = 100.86$, $df = 3$, $p < 0.05$) between the deviation from the power line trajectory in relation to the programmed routes in the four flights analyzed. The two flights made with FPV were, however, not significantly different (*Mann Whitney U Test*, $U = 116.9$, $p = 0.99$), whereas the two flights using autopilot differed significantly from each other ($U = 200.7$, $p < 0.05$).

The images obtained with both cameras clearly visualized white storks (*Ciconia ciconia*) both adults and nestlings, and 10 nests on the pylons (Figure 5). The size and position of the nests revealed high electrocution risk for the birds and for the power line to be damaged by fallen branches.

Fig. 2. Surveyed power lines with pylons geo-referenced by three different methods: (a) Dos Hermanas area, (b) Doñana area. Circle, from GPS at the base of the pylon; square, from sUAS using nadir-pointing camera; triangle, from sUAS using forward-pointing camera.

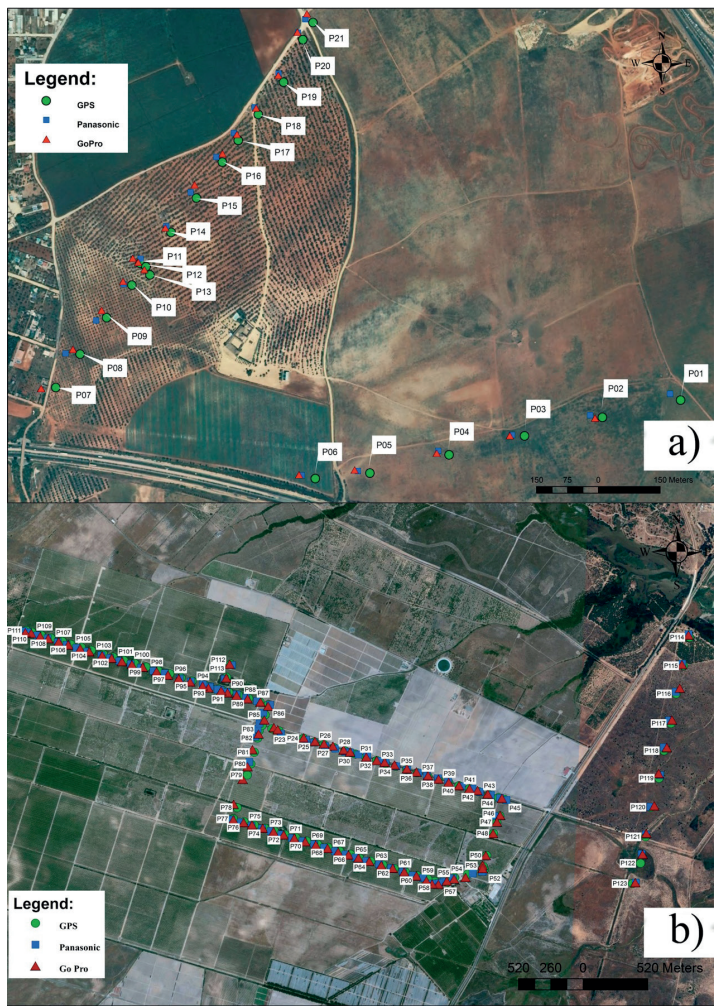


Fig. 3. Example of pylon designs recorded from the UAS (pylon designs classified following Clave 1992).

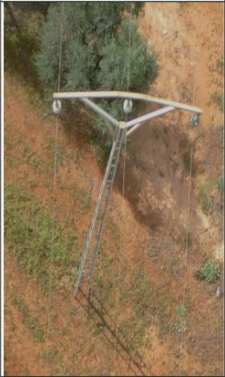
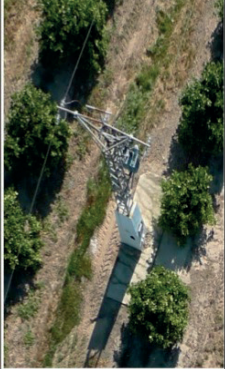
Pylon design	Ground	Front pointing camera	Ground pointing camera
Vaulted configuration with suspended insulators			
Pylons with strain insulators and jumper wires below insulators			
Triple-conductor circuit-breaker on pylon mast			

Fig. 4. Geo-referencing precision of the two types of cameras: (a) nadir-pointing; and (b) front-pointing.

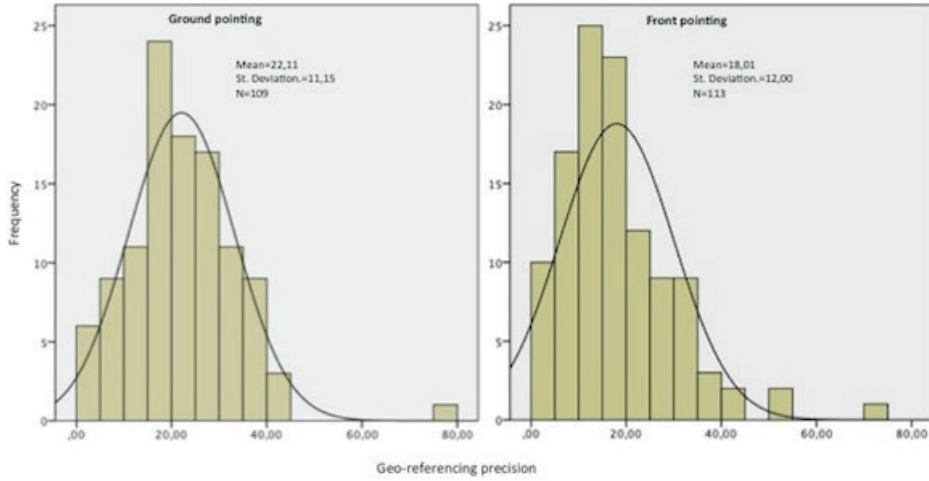
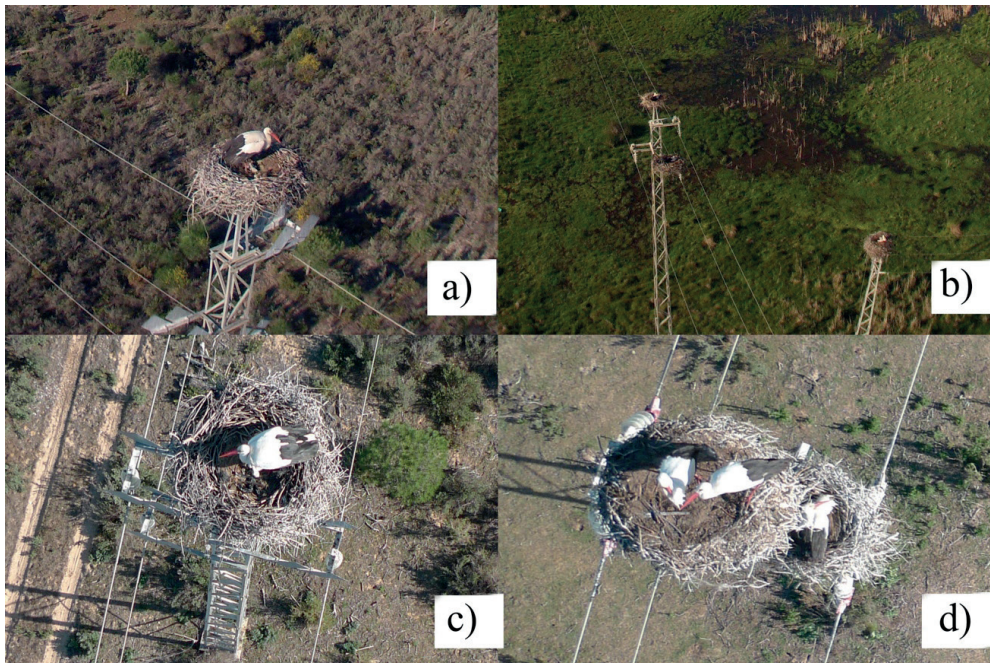


Fig. 5. White stork nests on the pylons: (a) and (b) recorded by forward-pointing camera; (c) and (d) recorded by nadir-pointing camera.



DISCUSSION

To assess the use of sUAS for power line monitoring, we performed a case study and overflew four power lines, identifying and locating the pylons and assessing their hazards to birds. We tested two cameras embarked in the sUAS, pointing forward and nadir. Both offered pictures with enough resolution to characterize different types of pylons, to detect corrective devices installed and to inspect bird nests built on them, although the nadir pointing camera offered the best quality images.

More than half of the pylons presented high electrocution hazard and the majority of the spans presented a moderate collision hazard for birds. The nests on the pylons presented high electrocution risk for the birds and for the power line to get damaged by the material of the nests. The UAS methodology provided valid geo-referencing precision for each pylon. The forward pointing camera technique was more precise than the nadir pointing one.

We tested two flight control methods: autopilot and FPV, and both acceptably tracked the power line. None-the-less, the FPV mode adjusted better to the line. For this reason, and keeping the low cost as a priority, we consider that it is more convenient to perform low altitude flights in FPV, with the plane operated by an experienced technician. Any drag can produce a deviation out of the track that will result in blurred pictures; it would reduce the precision of the geo-referencing or even a collision against the wires, with the consequent danger for both the plane and the power line. It is critical to fly in good meteorological conditions with the least possible wind (speed below 20 km/h) to minimize those risks. The autopilots market is improving and the prices are descending fast, so we foresee that autopilot results could be improved maintaining the costs in the near future (Rodríguez *et al.* 2012a).

SUAS have proved to be useful to study the design of power pylons and habitat types, the main goals for a typical bird hazard assessment. More information, such as bird density estimates or the presence of sensitive species in the area also would be helpful to make a more complete hazard evaluation of the lines (Ferrer *et al.* 1991; Ferrer & Janss 1999). Mortality surveys, which are also useful for hazard assignment, may be feasible by using sUAS, at least in open habitats and if conspicuous species are affected, or if the casualties are still hanging from the pylons or wires.

The main objective of our work was to develop a method that balances the cost, practicality, quality and effectiveness for bird hazard studies in power lines. There are more sophisticated sUAS available in the market that can fly longer distances, cameras that provide higher resolution images and software to automate line monitoring (Li & Ruan 2010). Additionally, the use of thermal cameras would also allow the identification of problematic points for operation conditions of the power lines, increasing the benefits of this approach for utility companies (Bologna *et al.* 2002; Han *et al.* 2009; Stolper *et al.* 2009). Any improvement in those characteristics would imply an increase in the overall costs, which is what we wanted to minimize, as the main objective for bird conservation is to invest the resources on pylons modification and not in the fieldwork.

The knowledge and skills needed for the correct and safe operation of sUAS is also of paramount importance. Most of the manufacturers would describe their planes as “user-friendly”, and that is true in the sense that it is not necessary to be a qualified pilot to use them. But, “remote control skills are needed for piloting, some knowledge is needed for maintenance and supervising, and even basic tasks as take offs can demand a certain level of athleticism from the operators” (Jones 2003). SUAS offer advantages over other power line surveillance techniques (see table 2 for a summary).

Table 2. Comparison of methods for power lines surveillance.

Method	Costs	Quality of the data for pylons' study	Availability and logistics	Other factors
Commercial satellite images	High	Low	Made to order.	Clouds can preclude images obtaining.
Conventional aircraft	High	High (depending on flying altitude and sensors quality)	Conditioned to favorable weather and proximity to an airstrip.	Need of specialized personnel. Risk for the plane crew.
Survey by foot or car	Medium	Very high	Conditioned to the accessibility and ownership of the area. Time consuming.	Bureaucratic process to access the farms.
Robots	High	Very high	Time consuming. Requires a lot of advance planning.	Not implemented realistically yet.
Small Unmanned Aerial Systems	Low	High (depending on flying altitude and sensors quality)	Immediate data collection. Conditioned to favorable weather and landowner permission.	Need of specialized personnel. Limited to UAS range.

Conventional aircrafts with automatic video surveillance systems (Whitworth *et al.* 2001; Ma & Chen 2004) provide high resolution images and can cover much more ground, but their use presents important drawbacks, as the risk for the crew and the need of an airfield in the proximity to take off and landing, that do not apply when using sUAS. In recent years there have been significant advances in the field of robotic automation that led to imaginative solutions for power line inspection (Katrašnik *et al.* 2008). Although this is a promising line of work, their use has not been implemented realistically in the field and their cost is high, being sUAS less expensive and more immediately available.

In the framework of unmanned aerial systems, rotary-wing platforms have been chosen for most of the engineering projects aimed at supporting utility companies that need high detail of wires conditions (Campoy *et al.* 2001; Peungsungwal *et al.* 2001; Ma & Chen 2004; Jones *et al.* 2005; Katrasnik *et al.* 2008; Li & Ruan 2010), because their ability to hover offers more stability than fixed-wing ones for taking high-resolution pictures. It is important to note, however, that wildlife managers do not tend to need such a level of detail for bird hazard assessment. The resolution provided by the commercial cameras of the types we used in our study is enough, and fixed-wing sUAS offer other advantages, as higher range and autonomy, pilot easy and, in the event of a malfunction or a crash, they are usually cheaper to repair than rotary-wing ones (see Table 2).

The effort and cost to characterize power lines in terms of bird protection largely depends on the extent and accessibility of the network, revision schedules, which varies according to environmental conditions and the durability of the materials employed. Line surveying costs are, however, significant. As an example, Ergon Energy, from Australia, declares to spend \$80 million a year on inspection (Li & Ruan 2010). In the Andalusia region (Spain), approximately 20% of the total budget spent in retrofitting dangerous distribution power poles to protect the endangered Spanish imperial eagle (*Aquila adalberti*) was the cost for identification of power pole design, which was around 500,000 € (López-López *et al.* 2011). It is important to point out that this kind of surveillance of the poles it is necessary not only during pole characterization prior to select which ones must be modified, but also a periodic survey of the anti-electrocution devices is needed. Limited life span of insulation protective devices requires periodic inspections to assure effective protection. Similarly, large bird nests on power poles require periodic surveys in order to prevent outages. Consequently, reduction in the total cost and time using sUAS would be greater.

As reference, for the sUAS inspection of the 12 km of lines surveyed for this study, 4 flights were needed. On each one of them, the two operators invested a total of 2 hours for the sUAS preparation, flight and data processing.

Our study is the first one demonstrating that low cost fixed-wing sUAS are a useful tool for power lines monitoring and offer advantages in cost and time investment versus other methods. Our system, valued at 7,800 €, has been able to geo-reference and characterize power lines providing the information needed to assess bird electrocution and collision hazard. Thus, their use can help to minimize the resources invested in the fieldwork phase of the work, to allocate most of the funds into actual corrective measures.

ACKNOWLEDGEMENTS

We thank Esteban Guerrero and Miguel Ángel Aguilar, the technician and pilot, respectively, responsible for the UAS. This study was conducted within the Projects: Aeromab, (Andalusia Government, Project for Excellence, 2007, P07-RNM-03246) and Planet (European Commission 7th FP Grant Agreement 257649). We also thank Manuela de Lucas, Marcello D'Amico and Manuela González for their reviews, and for providing valuable comments on this manuscript.

SUPPORTING INFORMATION FILES

-Figure S1

-Video: “power line inspection.mpg”

*"Africa, amongst the continents, will
teach it to you: God and the Devil are one".
Karen Blixen*

Chapter 2: Management of endangered species



[This Chapter is published as: Mulero-Pázmány M, Stolper R, van Essen LD, Negro JJ, Sassen T (2014) Remotely Piloted Aircraft Systems as a Rhinoceros Anti-Poaching Tool in Africa. PLoS ONE 9(1): e83873. doi:10.1371/journal.pone.0083873]

ABSTRACT

Over the last years there has been a massive increase in rhinoceros poaching incidents, with more than two individuals killed per day in South Africa in the first months of 2013. Immediate actions are needed to preserve current populations and the agents involved in their protection are demanding new technologies to increase their efficiency in the field. We assessed the use of remotely piloted aircraft systems (RPAS) to monitor for poaching activities. We performed 20 flights with 3 types of cameras: visual photo, HD video and thermal video, to test the ability of the systems to detect (a) rhinoceros, (b) people acting as poachers and (c) to do fence surveillance.

The study area consisted of several large game farms in KwaZulu-Natal province, South Africa. The targets were better detected at the lowest altitudes, but to operate the plane safely and in a discreet way, altitudes between 100 and 180 m were the most convenient. Open areas facilitated target detection, while forest habitats complicated it. Detectability using visual cameras was higher at morning and midday, but the thermal camera provided the best images in the morning and at night. Considering not only the technical capabilities of the systems but also the poachers' *modus operandi* and the current control methods, we propose RPAS usage as a tool for surveillance of sensitive areas, for supporting field anti-poaching operations, as a deterrent tool for poachers and as a complementary method for rhinoceros ecology research. Here, we demonstrate that low cost RPAS can be useful for rhinoceros stakeholders for field control procedures. There are, however, important practical limitations that should be considered for their successful and realistic integration in the anti-poaching battle.

Keywords: *Rhinoceros, poaching, remotely piloted aircraft systems, unmanned aerial systems, drones, illegal hunting, security methods, South Africa.*

INTRODUCTION

The two species of African rhinoceros, the black rhinoceros (*Diceros bicornis*) and the white rhinoceros (*Ceratotherium simum*) were driven to near extinction in the 1990's (Emslie & Brooks 1999). Numbers of both species are raising in Africa since 2007 (Knight 2011), but from 2010 the continued escalation in population growth has slowed down (Emslie *et al.* 2013), and the two species are still vulnerable, with white rhinoceros classified as Near Threatened and black rhinoceros listed as Critically Endangered according to IUCN criteria (Emslie 2012).

South Africa holds more rhinoceros than any other country in the world, with 83% of Africa's individuals, and also experiences the highest absolute levels of poaching, which is the main threat for their conservation (Emslie *et al.* 2013). Over the last years, and despite the anti-poaching efforts, there has been a massive increase in the number of rhinoceros poaching incidents. In 2010 there was an average of 0.9 rhinoceros killed per day; in 2011 it increased to 1.2; this number escalated to 1.8 in 2012, (resulting in 668 deaths along the year) and it has reached a staggering historical record of 2.2 per day in the two first months of 2013 (up to February 20th) (Emslie *et al.* 2013).

The rhinoceros poaching is a complex problem with multiple causes and potential solutions (Eustace 2012). Their horn is considered to be a traditional medicine for a variety of ailments in Asia (Lever 2004), with the highest demands from China, Hong Kong, South Korea and Southeast Asian countries, and it is used for ceremonial purposes in Yemen (Loon & Polakow 1997; Milledge 2007). Due to the high demand and the illegal nature of the trade, the prices fetched by the horn in the black market are high. This constitutes a temptation to rural people with scarce resources, as the market value of one horn-set may be equal to the salary of several years for the poacher (Eustace 2012).

There are various long and medium-term strategies in progress to reduce the illegal trade of rhinoceros horn, and they remain in constant discussion: horn control, legislation, cooperation with the horn purchasing countries, environmental education and rural development projects in rhinoceros areas, most of them conducted by public institutions or NGOs (Milledge 2007; Knight 2011). These general strategies are also supported by immediate anti-poaching actions in the field, directed by the management authorities or the landowners, and carried on by either park rangers or security companies.

In South Africa, around a quarter of the total population of rhinoceros live on private land (Knight 2011). The owners of these reserves and game farms are increasingly hiring specialized companies that focus on the protection of wildlife and the apprehension of poachers. The service of protecting valuable wildlife has led to an emergence of this type of business in recent years. They employ techniques based on operational methods of the police and armed forces. The basis of this strategy is to deploy ground based patrol units that spend multiple days tracking animals and poachers, and monitoring the fence lines for breaks. While the cost of employing these companies is high (around 10,800 € per year to maintain 1 guard patrolling 700-800 ha), they are the most popular alternative to reduce the number of poaching incidents in private land. Both private companies and public agents working in rhinoceros anti-poaching are demanding new technologies to increase their efficiency to detect and intercept poachers before a rhinoceros is killed. The need to be more effective in addressing the poaching problem was expressed by the IUCN/SSC African Rhinoceros Specialist Group (Knight 2011).

Discussions with security companies and conservation agencies have indicated that aerial monitoring may be of assistance in covering more ground, and remotely piloted aircraft systems (RPAS hereinafter) have been suggested to do this work (Eustace 2012). Some security firms already patrol the vast farms by flying twice a day with a micro light aircraft and directing the “boots on the ground” to the whereabouts of the rhinoceros.

Remotely Piloted Aircraft Systems (RPAS), sometimes also referred as Unmanned Aerial Vehicles (UAVs), Unmanned Aerial Systems (UASs) or drones (the ones for military purposes), are aircrafts (fixed or rotary wings) that are equipped with cameras and/or other sensors and can be sent (using manual, semi-automatic or automatic control) to a destination to gather information. These aircrafts act like an “eye in the sky” (Rodríguez *et al.* 2012a) with the operator at the ground control station receiving data or sending orders to the aerial platform. RPAS have been used for locating “enemies” in military applications for the last 20 years (Zenko 2013), and more recently they have started to play a role in many civilian tasks, including wildlife monitoring (Jones *et al.* 2006; Watts *et al.* 2010; Koh & Wich 2012; Rodríguez *et al.* 2012a; Sardà-Palomera *et al.* 2012; Vermeulen *et al.* 2013).

In this paper, we describe the use of a small low cost RPAS equipped with three different types of cameras to test their ability to support rhinoceros anti-poaching tasks in cooperation with a specialized security company working in the KwaZulu-Natal province of South Africa. We performed several flights in order to

test the technical capabilities of the system to detect rhinoceros, to reveal simulated poachers and to do fence surveillance. We evaluated the effectiveness of the system at different altitudes and times of the day and night, and over the two main habitat types in the area: open grassland and forest. Considering the most common *modus operandi* of poachers, we analyzed the aspects that affect remotely piloted aircraft's integration in anti-poaching operations.

MATERIAL AND METHODS

Ethics statement

At present, no regulations are in place for the use of RPAS in South Africa. Draft regulations pertaining to the use of UAVs have been published by the South African Civil Aviation Authority (SACAA) but these have not been ratified to date. The Recreational Aviation Authority of South Africa (RAASA) indicated that the flights could be performed as long as they were conducted over wildlife areas with low manned aircraft activity and not close to registered active airfields. The study therefore complies with the current South African legislation involving aviation safety. The RPAS operators had the required international radio operator licenses to operate in the frequencies used for this work.

To get an insight into the poaching problem, we met four people involved in rhinoceros protection at different levels. These interviews did not contain personal or ethically sensitive information, therefore ethics approval was deemed unnecessary by both the Ethics Committee of Animal Welfare of Doñana Biological Station (CEBA-EBD) and the Animal Ethics Committee (AEC - Faculty of Natural and Agricultural Sciences), a sub-committee of the Committee for Research Ethics and Integrity of the University of Pretoria. All four interviewed people provided their verbal informed consent to take part in the study once informed about the nature and objectives of the investigation. The participants gave their implied consent through cooperation and it was therefore deemed unnecessary to obtain written consent. All aspects of these personal communications were written down as part of the data collection process of the entire project. Ethics committee approval was deemed unnecessary to approve this consent procedure. We thank farm owners and the security company for providing valuable information used in this study, the lodging and the logistics for the field campaign.

Study area

The study area comprised 13 farms whose areas ranged between 1,500 and 25,000 ha, covering a total of 100,000 ha located in KwaZulu-Natal province, South Africa. The habitat on the farms is a combination of forest patches and grassland, and is utilized mainly for ecotourism and hunting. The rhinoceros population (both black and white) in the area is approximately 500 individuals. The field campaign was performed during August 2012.

Rhinoceros safety requirements definition

To define poachers' way of operation and actual anti-poaching surveillance methods, we separately met four people at the onset of the fieldwork: the security company manager, the rangers' coordinator and two rangers of the farms of the study area, all of them responsible for different aspects of rhinoceros safety.

Remotely Piloted Aircraft System description

-Airframe

The fixed-wing RPAS is a commercially available radio control plane airframe Easy Fly St-330 (St-models, China) modified by our team. It has a wingspan of 1,960 mm and a maximum take-off weight of 2 kg with a 350 g payload (Fig. 1). It has a maximum range of 10 km; an endurance of 50 minutes and it is launched by hand and landed manually in small patches of open terrain. It is propelled by a brushless electrical motor using a lithium polymer battery.

The plane is capable to operate in three different modes, and it is possible to switch from one to the next during the flight: automatic (using the abilities of the autopilot), FPV ("first person view mode") and manually (radio control conventional mode, also called "third person mode"). It is equipped with an onboard FPV video camera, a GPS (10 Hz, Mediatek, model FGPMMPA6B), a data-logger with a barometric altitude sensor Eagletree GPS logger V.4 (Eagletree systems, WA, USA) and an autopilot (Ikarus, Electronica RC, Spain) which provides flight stabilization and On Screen Display (OSD). The OSD provides GPS information about the position, speed, height and course of the aircraft. The data combined with the FPV video signal from the camera are sent to the ground station. For nocturnal flights we equipped the plane with a set of LED lights of different colors in the wings, nose and tail that allowed the pilot to locate and position the aircraft visually.

Fig. 1. Remotely Piloted Aircraft taking off.



-Ground control station

The ground station contains a monitor, a DVD recorder, a video receiver and a control signal transmitter with its associated antennas. It also includes a Laptop PC to program the autopilot, store the pictures and data logs, and decode in-flight telemetry, allowing tracking the position of the RPAS in real time on a Microsoft map (Redmond, WA, USA).

-Payload: Due to the RPAS payload limitations, only one of the cameras can be utilized on each flight.

1) Still photo camera: Panasonic Lumix LX-3 digital photo camera 11 MP (Osaka, Japan). It is integrated in the plane wing and aimed vertically to the ground. The camera is activated during the flight at the desired point using a mechanical servo. It is set in speed priority mode and in its widest zoom position.

2) High Definition (HD) Video Camera: GoPro Hero2 (Woodman Labs, Ca., USA). It has a field of vision of 127° and a resolution of 1080 p (1920 x 1080). The video camera is integrated in the nose of plane aimed forward and downwards, at an angle of 30° below the horizontal.

3) Long wave uncooled thermal video camera: the infrared camera module is a Thermoteknix Micro CAM microbolometer with a resolution of 640 x 480 pixels. The lenses of the module are interchangeable and tests were done with a focal length of 18.8 mm and 1.2 maximum aperture lens. This equates to a diagonal field of vision of 39.8° respectively. This camera can be integrated in the plane wing aimed to the ground at 15° nadir or in the same position but with at an angle of 30° below horizontal. Price of all the RPAS components is shown in table 1.

Table 1. Cost of the RPAS equipment (Material bought in Spain in June 2012)

Component	Price (€)
Airframe with the electronic system	1,000
Ground control station (antennas included)	6,000
Stills Photo Camera	450
HD Video camera	300
Thermal camera	6,000
Total	13,750

Experimental procedures

We conducted a total of 20 flights. On each flight, we passed over the targets at altitudes ranging from 10 to 260 m above ground level (AGL). Flight speed varied due to wind speed and direction, with a minimum of 15 km/h on the windiest days flying against the wind, up to 50 km/h when flying with tailwinds. In eight of the flights we mounted a still photo camera, eleven flights incorporated a thermal video camera, and only one incorporated a HD visual video camera. Four of those flights, with the thermal camera, were conducted at night, and the rest of them were performed during daylight.

Rhinoceros detection flights were done over approximate rhinoceros locations previously provided by rangers monitoring individuals regularly on the ground. Poacher detection flights were performed over areas where rangers and members of our team dispersed simulating poacher activity. We flew along the fences in first person view mode, which means using the real time video transmitted from the RPAS to the ground station, and the pilot guiding the plane manually using the transmitter.

Data analysis

Pictures obtained with the Panasonic LX3 camera were reviewed to identify rhinoceros, people or fences. They were geo-referenced using the information provided by the onboard Eagletree GPS logger V.4 (Eagletree systems, WA, USA) that includes a barometric altitude sensor. The software for geo-referencing is a customized extension that we developed with ENVI (Exelis Visual Information Solutions, CO, USA) that combines our plane position data with the pictures to generate GeoTIFF files. We projected the geo-referenced images using ArcGIS v.10 (ESRI, Redlands, CA, USA) to check that the whole desired area was actually covered.

The time invested in photo reviewing was 3.5 seconds per picture on average. To process each plane track took us 15 minutes and the geo-reference process was around 3 seconds per picture. One observer was able to do all the processing simultaneously, as he could first process the track, then start the geo-referencing program to run and do the review of the pictures while the geo-reference program was working. On average, an observer with a computer needed around 45 minutes to process a 500 pictures flight, which is the usual number of pictures taken per flight.

Overlapping of the images obtained depends on flight altitude and plane speed, and was calculated according to the equation:

$$O = \frac{k \times h - \frac{S}{P}}{k \times h}$$

Where:

O is overlapping (%),

h is altitude AGL (m),

S is speed of the plane (m/s),

P is the number of pictures the camera takes per second. $P = 2$ in our camera,

k is a constant that depends on camera's vertical sensor dimension. The equation to calculate it is:

$$k = \frac{dv}{f}$$

Where:

dv is vertical dimension of the sensor (5.6 mm in our camera)

f is local length (5.1 mm in our camera)

$k=1.09$ for the camera we used.

Spatial resolution of imagery depends on the altitude at which images are taken and the camera sensor's characteristics. With the camera we used, the relationship between altitude AGL and resolution was as indicated by Rodriguez *et al.* (2012):

$$R = 0.0416 \times h$$

Where R is Resolution (cm),

h is altitude AGL (m).

The area covered by the pictures can be calculated considering the flight altitude, the speed of the plane and horizontal dimension of the camera sensor.

$$A = \frac{S \times h \times k'}{10}$$

Where A is area covered by the plane / time (ha/h),

S is speed of the plane (km/h),

h is altitude AGL (m),

k' is a constant that depends on camera horizontal sensor dimension. The equation to calculate it is:

$$k' = \frac{dh}{f}$$

Where dh is horizontal dimension of the camera sensor ($dh=8.07$ mm in our camera).

f is local length (5.1 mm in our camera)

$k'=1.58$ for the camera we used.

Deviations from the horizontal plane, mainly produced by wind, caused some distortion in some of the pictures, but it did not affect our objectives. HD and thermal camera videos were reviewed to identify targets: rhinoceros, people or fences. We extracted video frames using Adobe Premiere Pro CS5 and improved their image quality using Adobe Photoshop CS5 (Adobe, CA, USA). Due to the forward and downward angle of the video cameras, it is not possible to project the video frames

horizontally on the map, but by contrasting the time corresponding to the frame with the plane track file, it was possible to place the targets with a 50 m precision.

Images analysis

We selected the pictures and extracted the video frames that contained targets. Many of them appear in consecutive pictures due to overlapping. To establish a reference altitude each time a target was detected, we chose the image in which the target appeared more centered on the picture area. If a target was overflowed more than once in the same flight but in several turns, the different detections were considered, as the observers who analyzed the images did not know the plane trajectory or the target locations, so they did not know if the targets were the same or different. If two targets were detected on the same picture, we classified them separately because the quality for each one can be different. Images were classified according to their quality following these criteria:

- High: the targets are detected and identified at first glance of the picture or video. Fence poles and wires are visible.

- Medium: the target is detected on a second or third review of the picture or video. To identify the target, it is necessary to zoom in, check other consecutive pictures, review the video in slow motion, or post process the picture or frame (modify the contrast or increase brightness). Fence poles are visible but wires are not distinguishable.

- Low: an object is detected but its identification is not possible. Fence trajectory is detectable but the poles or wires are not distinguishable.

We assessed the detection of the targets on each flight considering that they can be: 1) confirmed: when the target is identified with high or medium quality images and 2) not confirmed: when the target identification is not possible, either because the target could not be found at all or because the images had a resolution precluding identification.

Habitat type was characterized according to vegetation coverage in 100 m around each target location as: 1) Forest: vegetation coverage > 75%, 2) Grassland: vegetation coverage <75% and 3) Mixed: refers to the cases where the targets are located at the border between two farms. These locations have fences with maintenance trails along, so even presenting a high percentage of vegetation cover around, they could still be considered as open areas from a detectability perspective.

To facilitate the evaluation of the detectability according to time of day, we divided the flights in four periods related to light conditions: morning (07:00-10:15 h), midday (10:16-14:00 h), evening (14:01-17:45 h) and early night (17:46-20:00 h). Times are in South African local time. As a reference, in the study area, sunrise was from 6:31 h to 6:59 h and sunset from 17:44 h to 18:00 h, from August 1st to August 31st.

RESULTS

Poachers' modus operandi, poaching surveillance and rhinoceros monitoring (field interviews)

The people we interviewed provided very similar comments about their perception of poaching activities. This was not surprising as all of them work in the same area and deal with the same problem, although it is noticeable that the people at different work levels are able to provide detailed information about the whole poaching topic (from a general perspective to specific field issues), evidencing that there is a good information flow among rhino protectors.

The most common profile of a poacher is that of local people with low income and who obtain money selling the rhinoceros horns to the lowest levels of the syndicates. The poacher accesses the game farm on foot, sometimes accompanied by dogs, and generally there is an accomplice who drives him close to the fence and meets him at some point for collecting. Poacher entry hot spots onto the farms are generally through the same areas: near roads, trails, villages or known rhinoceros territories. The poacher enters the game farm either by cutting a hole in the fence, climbing over it, or crawling underneath it.

Poachers do not show preferences for particular times of the year, days of the week or time of the day, although there are some variations according to the season. Considering nights only, they show a preference for full moon nights (rather than dark nights) to enter the game farms, as increased lightness facilitates their movements. In summer there is more water available, and consequently the rhinoceros and the poachers are more dispersed, which makes it more difficult to detect them. In winter the rhinoceros gather near waterholes, therefore the poachers concentrate on the areas with available water and there is also less vegetation for camouflage. Time poachers spend inside the farm typically ranges from 3 hours up to two days.

The most common method for killing the rhinoceros is by shooting them with homemade or cheap firearms. Poison is also used in the form of anesthetic injected into apples or other fresh fruits that poachers leave close to waterholes used by rhinoceros. Snaring with thick wire or cable snares are also used but not on a regular basis.

Current monitoring of rhinoceros is generally based in aerial surveys (once per year) combined with GPS data of the animals provided weekly by field teams. Surveillance of farm perimeter is generally done every two days, or daily if there are poaching alert signals. Farm neighbor's cooperation on anti-poaching is generally well established, especially if they use the services of the same security company.

General surveillance procedure in our study area consists on 90 guards patrolling the 100,000 ha on a daily basis. Standard cost of poaching control including vehicles, fuel, materials and the rangers' salary, is about 900-1,000 €/ 700 ha/ month. An additional cost related to poaching is fence maintenance, done either by the landowner or by the security company. Fence maintenance cost can vary substantially from year to year and is not only associated with poaching but also with animal damage or natural deterioration. Other anti-poaching actions in which landowners and security companies are involved in include cooperation with wildlife surveillance teams and participation in environmental projects with local communities.

Flight data

We present a description of the results of the 20 flights and the scenarios where the targets were located in Table 2. No alarm reaction or flight responses were detected from any animals caused by the plane in any of the RPAS flights.

Table 2. Flights results

Camera	Time period	Time start	Time end	Target	Habitat	Result	Altitude (m) (Min-Max)
Still photo	Morning	09:03	09:26	People	Grassland, Mixed	Confirmed	32-149
				Fences	Mixed	Confirmed	40-175
		09:05	09:38	Rhinoceros	Forest	Confirmed	57
		09:42	10:02	People	Mixed, Forest, grassland	Confirmed	29-82
				Fences	Mixed	Confirmed	42-72
		09:52	10:12	Rhinoceros	Forest	Confirmed	31-137
	Midday	10:16	10:39	Fence	Mixed	Confirmed	50-175
				People	Grassland	Confirmed	123-158
		11:22	11:43	Rhinoceros	Grassland, Forest	Confirmed	38-239
	Evening	13:14	13:56	People	Forest	Not confirmed	
		17:19	17:38	Rhinoceros	Forest	Confirmed	82
				People	Grassland, Forest	Not confirmed	
Thermal video	Morning			Fences	Mixed	Not confirmed	
		07:51	08:11	Fence	Mixed, Grassland	Confirmed	27-155
				People	Mixed, Grassland	Confirmed	31-100
		08:21	08:55	Fence	Mixed	Confirmed	37-98
				People	Mixed	Not confirmed	
		08:27	08:56	Fence	Mixed	Not confirmed	
	Midday	09:25	10:03	Fence	Mixed	Confirmed	48-54
				People	Mixed	Not confirmed	
		10:27	10:46	Rhinoceros	Forest	Not confirmed	
		10:40	11:07	Rhinoceros	Forest	Not confirmed	
	Night	12:32	13:04	Rhinoceros	Forest, Grassland	Not confirmed	
		18:19	19:02	People	Grassland, Forest	Confirmed	12-125
				Fences	Mixed	Not confirmed	
		18:41	19:00	Rhinoceros	Forest	Not confirmed	
		19:17	19:40	Fence	Mixed	Not confirmed	
Visual video	Midday			People	Grassland	Confirmed	36
		19:27	19:45	Rhinoceros	Grassland	Not confirmed	
Visual video	Midday	11:08	11:27	Fences	Mixed, Forest, Grassland	Confirmed	10-17
				People	Mixed, Forest, Grassland	Confirmed	10-35

We provide the minimal and maximum altitude at which a target was confirmed in each flight. When only one value is presented it means that the target was located just once.

Still photo camera data

The pictures covered the area overflowed by the plane with an overlapping between 36.3% in the flights at highest speed and lower altitudes (10 m AGL and 50 km/h) and 99.2% at lowest speed and highest altitude (260 m AGL and 15 km/h). As an example, flying during one hour, at an altitude of 150 m and a speed of 30 km/h we were able to cover 711 ha. Resolution varied from 0.4 cm in the pictures obtained at the lowest altitude to 11.8 cm resolution at the highest.

Rhinoceros were easily detected in both grassland and forest habitats at a minimal altitude of 31 m and a maximum of 239 m AGL (Fig. 2). People simulating poachers were identified in a wide range of altitudes from 29 to 158 m in grassland and forest habitat, although it was more difficult to distinguish some individuals in the forest, especially certain rangers in camouflage clothing because they offered less contrast with the surroundings. Fence surveillance results were acceptable at morning and midday hours, with the pictures presenting enough quality to zoom in and find people along it. At the lowest altitude (40 m) it was also possible to detect footprints in the sand, but the quality was not sufficient to check the condition of the fence wires along the entire fence route. (Fig. 2)

Fig. 2. Images obtained with still photo camera. Left: Two rhinoceros (altitude 44 m AGL) in grassland habitat. Right: two people accompanied by two dogs near the fence (altitude 123 m AGL). These images were classified as “high quality”.



The quality of the images was best at midday (80% of the pictures had high quality in this time period) with vertical sunlight, and the results were worse when the

shades of the trees produced dark areas, which happened in the morning (66% high quality) and in the evening, when this effect is accentuated because the air is less clean causing a blurry effect (100% medium quality pictures).

Video data

The HD video camera provided good resolution below 40 m AGL, but due to the wide angle of the lens (fov 127°), flights above 50 m altitude AGL had not enough quality to identify people or to survey the fences. These results led us to cancel the planned flights for rhinoceros detection, as we considered the altitude had to be so low to identify objects that it could be dangerous for operating the airplane and might also disturb the rhinoceros. (Fig. 3 and Video S1 in supplementary material)

Fig. 3. Frame extracted from HD video. People and car near the fence. This image was classified as “high quality”.



The thermal camera provided the finest images in the early morning, when the ground was coldest and there is more contrast between it and any animal or person. We confirmed the presence of targets at altitudes as high as 155 m, but in general, it was difficult to identify them at the species level, as they appear in the video as diffuse (although very contrasting) white spots. Only 5% of the images taken with this camera presented high quality, 24% medium and 71% low. At the earliest hours of the night, the results obtained did not allow us to confirm that any of the spots we

detected when overflying a rhinoceros was actually a rhinoceros, and low altitude was needed to identify the people using details such as body shapes. After hours of working with thermal video and “training the eyes” we noticed a considerable improvement on detection and shapes identification. Resolution offered by the thermal camera was enough to follow fence posts and to detect individuals, but fence wires were not distinguishable at all. (Fig. 4 and Video 2 in supplementary material)

Fig. 4. Frames extracted from thermal video camera. Left: A person near the fence (medium quality image). Right: two giraffes captured during one of the flights. Although giraffes were not the targets of our study, this image may serve as an example of the quality of thermal captures when thermal contrast is high.



DISCUSSION

Rhinoceros poaching is a pressing issue that needs immediate solutions in the field. Rhinoceros stakeholders are demanding new technologies (Knight 2011); social media have already suggested the use of drones (Wild 2013) and WWF announced in 2012 that it sponsors an on-going remotely aerial survey system and anti-poaching program in cooperation with Google to protect tigers, rhinoceros and elephants (WWF 2013). RPAS have already proved their efficacy for military and civil applications in general, and wildlife monitoring in particular. Now the question is how to integrate RPAS in rhinoceros anti-poaching tasks. To answer this question there are

two main aspects to consider: capabilities (technical and practical) and current limitations.

Technical considerations

The still photo camera provided the best results in terms of image quality (94% of the pictures taken by this camera allowed us to confirm the targets) and precision in the location. That is why this is the most attractive and currently the method of choice in conservation biology studies (Chabot & Bird 2012; Getzin *et al.* 2012). However, it is a relatively slow procedure, as images must be downloaded after RPAS lands and then reviewed and post processed. Even if pictures were transmitted in real time to the ground station (which is technically possible) accelerating the process, it would still take time to review them. Therefore, the use of a still photo camera would not be suitable to support real time anti-poaching tasks like poachers location during a pursuit. A positive aspect is that still photos would be the best method to provide image proofs against poachers because it offers the best resolution.

Video offers real time data, so it seems a better option than still images for poaching control. It is recommended to use a video camera with a narrower view field and zoom capabilities to identify the targets at safe altitudes (over 100 m AGL) in real time with enough magnification. Although video offers less precision on target location, according to the interviews with the people involved in rhinoceros safety, accuracy is not so important for anti-poaching purposes, or at least it is less important than immediacy.

As far as we know, this study offers the first nocturnal tests for wildlife monitoring using thermal cameras onboard a fixed-wing small RPAS, which is the only option for RPAS nighttime surveillance. The camera we used provided acceptable results when flying low, but the quality does not guarantee to identify some targets and it is possible to miss some, even one as conspicuous as a rhinoceros, when thermal contrast is low or flying at high altitudes. 29% of the thermal images allowed us to confirm the targets, and the rest presented low quality, precluding identification. It is important to consider that the last are still useful, as in a real anti-poaching situations, the dubious objects could be further inspected either overflying lower the RPAS or by other means (as ground patrols). Additionally, the quality and resolution of the thermal sensor can be improved and therefore the detection.

As expected, habitat type had an influence on target detection, which is more noticeable when using visual cameras, either video or still photo. Although rhinoceros are large enough to be detected from high altitudes with still photo cameras, people, especially if wearing camouflage clothes or hidden under a thick tree may not be detectable if flying at high altitudes.

Time of day had an influence on target detection. Our results indicated that best time for the use of visual cameras was from early morning to midday, and decreased along the evening. Thermal camera provided better results when temperature contrast is higher (Israel 2011), mainly at early morning and night. The detectability limitation linked to the hourly cycle, which is related to light conditions and air-ground thermal contrast, is important, as this means that the usefulness of RPAS as monitoring tools does not remain constant throughout the day. This effect would be accentuated when the temperatures are higher and humidity increases, as we would expect in the area where we performed the tests during summer, or in places with high humidity levels (tropical or coastal areas).

There is a compromise in deciding flight altitude for anti-poaching. Lowest altitudes provide the best results in terms of image or video resolution, but the surveyed area is smaller. Flying low implies more risk for the plane in case of failure and easier detection of the plane from the ground (therefore disturbing the rhinoceros or being more easily detected by poachers). Our results suggest that an altitude range between 100 and 180 m AGL is suitable for detecting rhinoceros or people, and to do fence surveillance with acceptable quality levels, it is a safe altitude for the plane and it is not very noticeable from the ground.

Practical considerations

Considering poachers *modus operandi* and current security procedures, there are some limitations for the integration of RPAS in routine anti-poaching work in a realistic and efficient manner.

Legal aspects

South Africa, as with many other countries in the world, does not yet have a legal framework for operating unmanned aerial systems. The absence of regulation for flying beyond line of sight constrains the range of work of the aircrafts, strongly limiting the actual technological capacities of the systems to just short range operations of RPAS operated by manual radio control (SAMAA 2001), as the ones we

presented in this paper. Some authors already addressed this issue arguing that operations that do not pose a safety threat to humans in the air or on the ground should be permitted (Ingham *et al.* 2006). They suggested Light UAVs for poaching site surveillance and proposed ideas including UAV corridors, avoiding inhabited areas and frequently used airspace, all in order to fly these aircrafts safely. We support these proposals, as rhinoceros distribution coincides with very low populated areas where the risk of hitting a person or crashing with another aircraft or infrastructure is low, especially flying at altitudes below 300 m AGL. The South African Civil Aviation Authority (SACAA) has published draft UAS regulations (SACAA 2008; Mamba 2009) that include exceptional permits for public interest uses of UASs (as anti-poaching could be classified). However, to date there has been no official notice that the SACAA has approved any protocol for UASs flights.

Scale of work and range

Scale of work is a limiting factor in using RPAS for anti-poaching tasks. The territories rhinoceros inhabit are large and population density is low (1 rhinoceros/200 ha on average in our study area). We demonstrated that it is possible to have an “eye in the sky”, but this eye cannot look everywhere all the time, so that logistics have to be evaluated. How many eyes are necessary and how often do they have to look? The management and application of a RPAS or multiple RPAS is a key question that rhinoceros safety stakeholders need to consider and define before planning RPAS use.

Small low cost RPAS typically fly for 30-40 min and their range is limited up to 10-15 km. Roughly considering that a RPAS flying at 150 m AGL could cover 711 ha, to survey the 100,000 ha of our study area would take around 140 hours (5.8 days). And that excludes the time to move the Ground Control Station from one point to another, taking off and landing, changing and charging the batteries, data processing, and assuming 24 hours personnel availability. Obviously, that time would be reduced if having more RPAS available, but that would entail higher associated costs.

There is a compromise between the area to control and the frequency of this control. A reasonable solution would be to focus RPAS for monitoring hot spots: either rhinoceros preferred locations or most sensitive poaching areas, which are generally known by security companies or park rangers, or areas where access by anti-poaching patrols and/or vehicles is complicated by other factors such as difficult terrains etc.

Weather conditions

Small RPAS are safe to fly up to 15-20 km/h wind speed. They are not suitable to operate in rainy conditions because the electronics can be damaged and the data obtained by the cameras in low light levels would not be useful.

Temperature and terrain altitude affect air density, which influences the power needed to fly the plane, aircraft battery consumption and consequently endurance and range. These variables also influence the power required for takeoff, which is higher the colder it is, or in higher terrains. This can also translate into more failed takeoffs. In experiments performed for other purposes, we found that our system lost 10 minutes of endurance (around 30%), when comparing sea level in summer in Spain to winter at 2,000 m in South Africa.

RPAS possible negative effects

Rhinoceros did not show any alarm or discomfort reactions during our flights. However, there is no proof that RPAS could not disturb them or other animals if their use is continuous, so further investigation of this aspect is needed. Some farms that have rhinoceros also offer ecotourism activities that bring important income. Therefore, visitor acceptance to the presence of RPAS in those areas would be important.

Choosing the right RPAS

The range of RPAS available is extensive and growing by the day. From micro systems that fit in the palm of a hand up to 2 tons airplanes, there is a huge variety in market offer. Considering the scale of work, the funding limitations and the sensor requirements, “close range” (Blyenburgh 1999) RPAS seem to be the best choice for anti-poaching purposes.

RPAS’ users always want to improve system performances to maximize endurance, range and sensors capabilities (data quality), and to minimize another set of characteristics associated with the RPAS: price (of the system and spares), logistics (size, transportation, taking off and landing requirements), and experience level needed for its operation. Unfortunately, any improvement in the system performances entails an undesirable effect in one or more of the second set of characteristics that would make RPAS less affordable or practical. Thus, the most suitable choice is a balanced compromise the user has to accept considering all the pros and cons for his specific purposes.

Costs and benefits

The recommended close range RPAS are typically lighter than 5 kg, have 30-45 minutes endurance and offer an operational range between 5-20 km. The price, capacities and reliability vary according to the manufacturer. In general, there is an investment in a whole system, composed by the ground control station, antennas, and two or three planes that need to be repaired or substituted when they reach a certain number of flights. As a reference, the system we used has performed more than 500 flights with an approximate total investment of 14,000 € including the sensors payload (see Table 1). There are more affordable options available in the market, but from our experience, reliability of some very cheap components like servos, batteries or even tripods is not guaranteed and their failure may cause serious problems affecting expensive components, so it is worth to get at least medium quality spares.

The benefit of integrating RPAS in anti-poaching work is difficult to evaluate in economic terms, as its calculation would involve to put a price on the life of a rhinoceros and to evaluate how many could be saved by using RPAS. It has been pointed out (Ferreira *et al.* 2012) that white rhinoceros carry two types of values: a commercial value (live rhinoceros trade and rhinoceros hunting) and a conservationist or aesthetic value. The first one could be calculated (white rhinoceros average price in 2012 was 17,330 €, record price in 2012 was 53,784 €; black rhinoceros record price in 2012 was 44,969 €) but the second one is hardly translated into numbers. Currently there is not real work using RPAS to be able to estimate the number of rhinoceros that could be saved by RPAS use or to calculate other types of surveillance costs that might be reduced by using this technology. As a reference, the investment needed for a small low cost RPAS (including spare platforms, spares, tools, etc.) that could last for about two years being used weekly (around 30,000 €), plus around 6,000 € to train operators, could be assumed by a medium size security company or institutions that control areas between 50,000-100,000 ha (Security company manager, pers. comm.). The business of anti-poaching is growing, especially in private land, with the result that RPAS will be not only appreciated for their real usefulness, but also as a competitive asset for those companies that include them in their surveillance programs.

RPAS integration in anti-poaching tasks

Considering both the technical and practical aspects we propose three alternatives for RPAS integration into anti-poaching work:

1-As a secret tool for surveillance. Security companies and public entities could use RPAS as a “hidden” tool to monitor systematically poaching hot spots or sensitive areas in order to get data, detect intruders, check rhinoceros presence and safety, as well as provide evidence that could be used on court against poachers. In this case, RPAS must be as discrete as possible. This would entail minimize the noise and camouflage the plane itself and to prevent locals to know about its use.

2-As a supporting tool during poaching incidents. The role of RPAS could be to support ground patrols during the pursuit of poachers, providing real time information about suspect numbers, locations and movements. Images taken may be used as evidence in court if needed. RPAS require less logistics than conventional aircraft, but they still do require some. For this type of very immediate use, technical efforts should be concentrated on developing mobile units integrated in small trailers or 4x4 vehicles that could permit a fast deployment.

3-As a deterrent tool. Security company managers suggested that by making widely known that the area is under constant vigilance by RPAS, it would discourage locals to poach. That would include performing demonstrations to the local communities and appearing in media with awareness campaigns, which could make them afraid and aware that they can be detected even without notice. In this case, it would be convenient to focus the effort with RPAS on farm perimeters surveillance and to get proof of irregular use of the area, giving media coverage to them.

The three alternatives may be combined in different times or areas to optimize the use of the system. For example - keep RPAS use secret until they contribute to catch a poacher and then publicize it widely in the local area.

There is also a fourth use for RPAS, not related to poaching but also involving rhinoceros conservation. RPAS can provide quasi-real time information of habitat changes affecting species movement behavior (Rodríguez *et al.* 2012a). Thus, combining high-resolution images of the areas with individuals' locations, RPAS can contribute to answer ecological questions that have been identified as key conservation factors, such as population density, nutrition and diet (Knight 2011).

We also foresee a promising field of work using other sensors (like static surveillance cameras and movement detectors) that could work together with RPAS forming an heterogeneous cooperating objects network for sensitive areas surveillance.

CONCLUSIONS-MANAGEMENT IMPLICATIONS

Our study is the first approach using remotely piloted aircraft systems for anti-poaching tasks and it can be expanded to other areas or species that suffer from the same problem. Some other African and Asiatic countries have rhinoceros poaching problems too, (Milledge 2007; Martin & Martin 2010) and large mammals such as elephants also suffer from illegal hunting (Dublin 2011). We have demonstrated that current low cost RPAS present enough technical capabilities to provide useful data, but there are also important practical and technical limitations that must be considered, evaluated and solved by users and authorities before these systems can be deployed in a realistic way (see Table 3 for a summary of the best and worst scenarios). The role RPAS can play in anti-poaching should not be overestimated and investment in this technology should be proportional to the results obtained because the resources for rhinoceros conservation are limited.

Table 3. Best and worst scenarios for the use of RPAS in rhinoceros anti-poaching.

Characteristics	Best scenario	Worst scenario
Flight altitude	< 100 m	> 100 m
Range for low-cost RPAS	< 15 km	>15 km
Time period for visual camera	Morning-midday	Evening
Time period for thermal camera	Morning-night	Midday-evening
Meteorology	Wind < 15 km / h	Wind > 15 km / h
	No rain	Rain
	Dry areas	Areas with high humidity
Habitat Characteristics	Open habitats	Thick forest
	Non populated areas	Populated areas
	Low altitude areas	High altitude areas

ACKNOWLEDGEMENTS

We thank farm owners and the security company (who preferred to remain anonymous due to commercial reasons and their rhinoceros' safety) for providing valuable information used in this study, the lodging and the logistics for the field campaign. We also thank the logistical support provided by the Centre for Wildlife Management, University of Pretoria and CSIR during the campaign. We are grateful to Esteban Guerrero and Miguel Ángel Aguilar, the technicians of the Aeromab and Planet projects, who piloted the aircraft and worked in data processing. Additionally,

we wish to thank Airam Rodríguez, Marcello D'Amico and Manuela González for their reviews and for providing valuable comments on this manuscript.

SUPPORTING INFORMATION FILES

-Video S1: “fence surveillance HD video.mpg”

-Video S2: “thermal camera video”

"He learned to communicate with birds and discovered their conversation was fantastically boring. It was all to do with wind speed, wingspans, power-to-weight ratios and a fair bit about berries." Douglas Adams

Chapter 3: Conservation in a human dominated landscape



[This Chapter is published as: Rodríguez A, Negro JJ, Mulero M, Rodríguez C, Hernández-Pliego J, et al. (2012) The Eye in the Sky: Combined Use of Unmanned Aerial Systems and GPS Data Loggers for Ecological Research and Conservation of Small Birds. PLoS ONE 7(12): e50336. doi:10.1371/journal.pone.0050336]

ABSTRACT

Technological advances for wildlife monitoring have expanded our ability to study behavior and space use of many species. But biotelemetry is limited by size, weight, data memory and battery power of the attached devices, especially in animals with light body masses, such as the majority of bird species. In this study, we describe the combined use of GPS data logger information obtained from free-ranging birds, and environmental information recorded by unmanned aerial systems (UASs). As a case study, we studied habitat selection of a small raptorial bird, the lesser kestrel *Falco naumanni*, foraging in a highly dynamic landscape. After downloading spatio-temporal information from data loggers attached to the birds, we programmed the UASs to fly and take imagery by means of an onboard digital camera documenting the flight paths of those same birds shortly after their recorded flights. This methodology permitted us to extract environmental information at quasi-real time. We demonstrate that UASs are a useful tool for a wide variety of wildlife studies.

INTRODUCTION

Biotelemetry (or bio-logging science) enables the remote measurement of data pertaining to free-ranging animals using attached electronic devices (Cooke *et al.* 2004; Ropert-Coudert & Wilson 2005). These devices are becoming increasingly sophisticated, monitoring behavioral, physiological and even some environmental parameters, and linking them to spatio-temporal movements (Moll *et al.* 2007; Rutz & Hays 2009). As such, biologgers have become a fundamental tool for the development of an emerging discipline called “movement ecology”, aimed at studying all kind of movements by all kind of organisms (Nathan 2008).

Currently, GPS data loggers constitute the lightest devices providing accurate spatio-temporal records, but its use is mainly constrained by the fact that most of them need to be retrieved after deployment to download the data and by battery size (the heaviest part of these devices). Small batteries are exhausted quickly, giving information during a short period of time. Unfortunately, given the relatively heavy mass of some of these devices, high-resolution telemetry still is a technological challenge for field biologists working with small animals (Cooke *et al.* 2004; Moll *et al.* 2007). As a rule of thumb in birds, devices should weigh, 3–5% of the bird’s body mass (Kenward 2001), but the majority of bird species have a body mass lower than 100 g, and the mean mass for 6.000 species is estimated at only 37 g (Blackburn & Gaston 1994). At present, and with currently available GPS devices weighting several grams, a plethora of studies tracking detailed movements of just large bird species, such as raptors (Shepard *et al.* 2011; Duerr *et al.* 2012) or seabirds (Zavalaga *et al.* 2011), are being published. This is seriously skewing our knowledge of movement strategies, and thus home range dimensions as well as total daily distances travelled by non-migratory individuals in the Class Aves.

A new generation of biologgers, known as animal-borne video and environmental data collection systems (AVEDs), have been heralded as the latest revolution in the tracking of wild animals as, in principle, these systems would enable researchers to see what the animal sees in the field (Moll *et al.* 2007; Bluff & Rutz 2008). A word of caution has also been raised regarding the cost/benefit ratio of some of these systems, and their applicability (see Millsbaugh *et al.* 2008; Rutz & Bluff 2008; Bluff & Rutz 2008). In the case of birds, the species that have carried AVED’s for research purposes include large seabirds (Sakamoto *et al.* 2009; Grémillet *et al.* 2010) and crows (Rutz *et al.* 2007), all of which are well above the mean size in Class Aves (Blackburn & Gaston 1994). Therefore, the combination of spatio-temporal data

with other data provided by biotelemetry (e.g. environmental information) is not feasible for small sized animals (Moll *et al.* 2007).

Unmanned aerial systems (UASs) may constitute a useful complement to retrieve environmental data (Jones *et al.* 2006; Watts *et al.* 2010), and can be especially interesting for small animals where other techniques involving more weight cannot be applied. Low cost UASs have recently undergone an intense development, leaving the realm of technological wars to become an affordable (Table S1), safe and user-friendly option for a wide variety of wildlife studies (Jones *et al.* 2006; Watts *et al.* 2010; Sardà-Palomera *et al.* 2012).

In this paper, we describe the combined use of GPS data loggers and environmental information recorded by UASs to study habitat selection of a small bird species, the lesser kestrel *Falco naumanni*, living in a highly dynamic landscape. After downloading the spatio-temporal information from the kestrels, we programmed the UASs to fly and document with pictures the paths of those same birds shortly after their flight, extracting environmental information at quasi-real time that we used to study the availability of different habitat types along the bird flightpath. Therefore, obtaining high-resolution images becomes a useful monitoring technique to study habitat selection and/or foraging behavior that can provide invaluable information for conservation and management (BirdLife International 2011), specially in situations in which foraging decisions may be dependent on structural changes in highly dynamic landscapes.

Table S1. Budgetary cost of the equipment used in this study.

Component	Price * (€)
<i>Teflon ribbon back-pack</i>	30
<i>GPS data logger</i>	800
<i>Aerial platform</i> (including electronics onboard, GPS, autopilot, stabilization system, FPV camera, Eagle tree with barometric sensors)	1000
<i>Payload</i>	
Panasonic Lumix LX3	450
<i>Antennas and tripods</i>	
Video	1500
Control	400
<i>Ground Control Station</i> (including laptop, monitor and connecting wires)	1500
Total	5680

* Prices paid in Spain in 2011, in Euros. It may vary depending on location.

MATERIAL AND METHODS

Ethics statement

This study has been carried out in accordance with EC Directive 86/609/EEC for animal handling and experiments, and with the current Spanish legislation involving aviation safety. The Regional Government (Junta de Andalucía) approved permits to access to the sampling sites and the animal handling procedures. The Ethics Committee on Animal Experimentation from Doñana Biological Station approved the research plan of HORUS project.

Study species

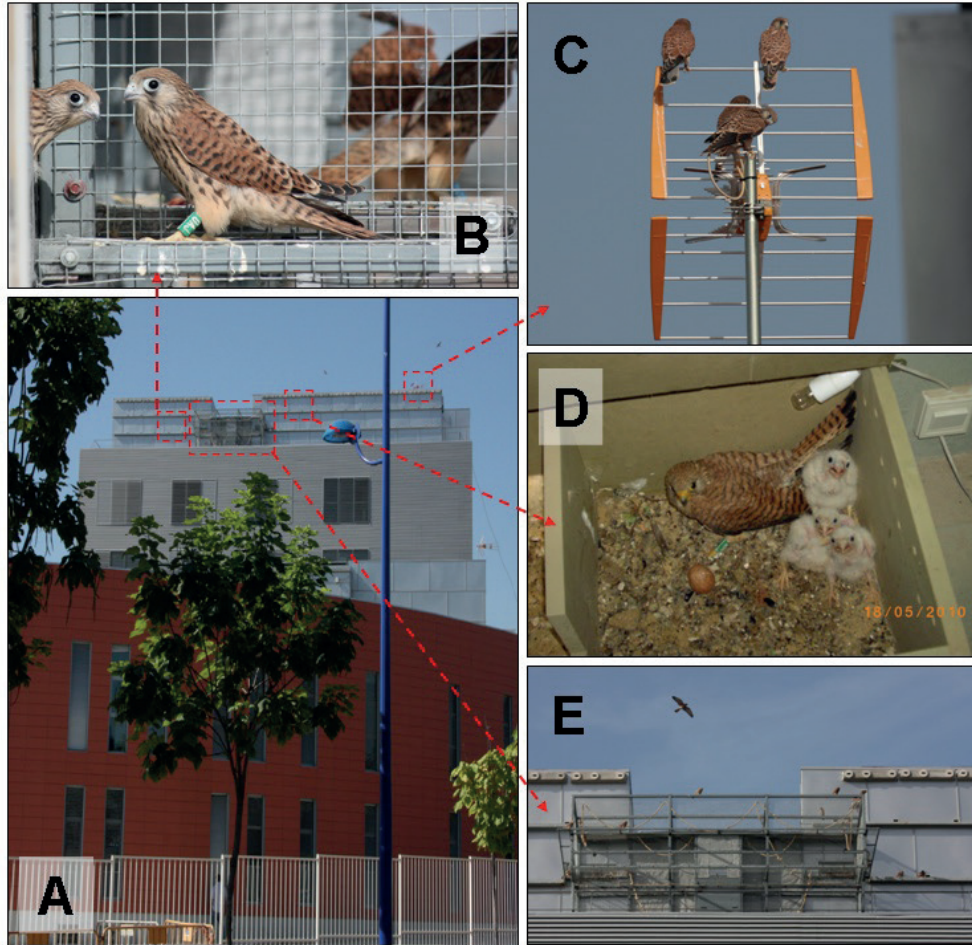
Our model species, the lesser kestrel, is one of the smallest European raptors (wing-span 58–72 cm, body mass 120–140 g). It feeds mainly on insects (i.e., grasshoppers, beetles, crickets), but also on small mammals (Pérez-Granados 2010; Rodríguez *et al.* 2010 and references therein). Its population suffered a severe decline (estimated at more than 30% of the world population) during the second half of the 20th century. However, the population has been considered stable for the last two decades, and consequently, it has been recently downlisted from ‘Vulnerable’ to ‘Least Concern’ according to IUCN criteria (BirdLife International 2011). Presumably, the main cause of the decline of the lesser kestrel in western Europe was habitat loss and degradation as a result of agriculture intensification (BirdLife International 2011). During the chick rearing period, lesser kestrels select field margins and cereal field as foraging areas (Tella *et al.* 1998; Franco *et al.* 2004). In addition, kestrels associate with grain harvesters to catch the arthropods flushed by these machines. One of the most important structural changes associated with agriculture intensification is field enlargement, and consequently, the reduction of field margins (Rodríguez & Wiegand 2009). Likewise, the use of machines to harvest cereal fields has reduced the time of harvesting at a locality to just some weeks or days. So, both factors are concurrently limiting kestrel foraging opportunities.

Study area

Due to the lesser kestrel decline and also for research purposes, several breeding programs have been put in place in Spain in recent years (Pomarol 1993; Negro *et al.* 2007; Alcaide *et al.* 2010). One of these reintroductions was carried out in

the roof of our own institute (Doñana Biological Station, Seville, Spain), where we conducted this study. In 2008, a hacking program was started releasing to the wild a total of 149 nestlings (51, 58 and 40 in 2008, 2009 and 2010, respectively) originating from a captive breeding program (DEMA, Almendralejo, Spain, www.demaprimilla.org). In addition, injured adult birds (1–4 individuals) were maintained during four breeding seasons (2008–2011) at an external cage (6x2x2 m) to facilitate conspecific attraction at the colony. Breeding pairs established themselves at the colony after the second year (one, three, six and three breeding pairs in 2009, 2010, 2011, 2012, respectively). The colony is formed by two elongated constructions on the roof of a five-floor building. Forty wooden nest boxes with sliding doors to capture the birds at the nests from inside the building are open to the north wall (see Figure S1). Although the colony is located within the urban area of Seville, it is in the northernmost edge of the city facing agricultural fields and the communication ring of the city (highways, railroads, and a high density of powerline corridors). Agricultural fields extend toward the northwest, the nearest ones being no more than 500 m away from the colony.

Fig. S1. Lesser kestrel breeding colony located at the headquarters of Doñana Biological Station (Seville, Spain). A) Lesser kestrel colony located at the roof of the headquarters of Doñana Biological Station in Seville. B) Nestlings in the proximity of releasing nest-boxes. C) Fledglings perched in one of the antennas of the building. D) First breeding attempt as seen from the inside of the colony structure. E) Cage with adult birds inside and fledglings resting outside.

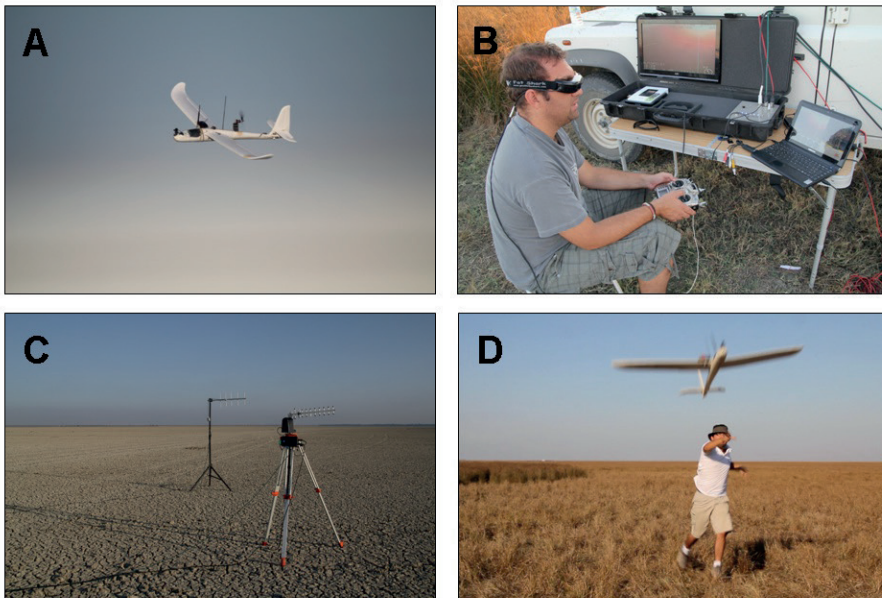


Unmanned Aerial Systems (UASs)

The aerial platform was built into a ST-model Easy Fly plane (St-models, China) with a wingspan of 1.96 m and a weight of about 2,000 g (Figure S2). It is

propelled using a brushless electrical engine (lithium polymer battery). The UAS was controlled from a ground station using a long-range radio control system. It carried an onboard video camera, a GPS (10 Hz, Mediatek, model FGPMOPA6B), a data logger with a barometric altitude sensor Eagletree GPS logger V.4 (Eagletree systems, WA, USA), an Ikarus autopilot (Electronica RC, Spain), which provided flight stabilization and On Screen Display (OSD), and a Panasonic Lumix LX-3 digital photo camera 11MP (Osaka, Japan). The camera was integrated in the plane wing aimed to the ground, and was activated using a mechanical servo, set in speed priority mode and in its widest zoom position. The Ikarus OSD provided GPS information about the position, speed, height and course of the aircraft. These data were combined with the video signal from the camera and sent to the ground station in 2,4 GHz. The autopilot provides stabilization of the aircraft, waypoint following capability (including altitude) and an “emergency return home” function. The take-off and landing of the plane is by manual control. The ground station is composed by a monitor, a DVD recorder, the video receiver and the control signal transmitter with their associated antennas. It also includes a Laptop PC to program the autopilot, to store the pictures and data logs, and to decode in-flight telemetry allowing to track the position of the UAS in real time on a Microsoft map (Redmond, WA, USA).

Fig. S2. Unmanned Aerial System equipment and operation. A) Aerial platform. B) Ground station. C) Antennas of control signal transmitters. D) Manual take off.



Experimental procedures

During the 2011 nestling period (June–July), we fitted 5 g GPS data loggers to both members of two breeding pairs of kestrels using Teflon ribbon backpack harnesses (Micro size, TrackPack, Marshall Radio Telemetry, North Salt Lake, Utah, USA). Two GiPSy2 GPS data loggers (2361566 mm, 1.8 g plus 3.2 g battery, Technosmart, Italy) were programmed in continuous mode (1 fix/ sec) for a four hour period. To avoid monitoring abnormal behavior due to capture stress and harness fitting, birds were first captured and fitted with a harness and a 5 g dummy GPS data logger. One week later birds were recaptured and the dummy substituted by a real GPS data logger programmed to start recording data the next day after recapture. To download the data from the data loggers, birds were recaptured at their nest boxes when they were delivering food to their nestlings, after batteries were exhausted one day later.

After the download of the bird tracks, six flights were made by the UAS. Three of them with the aim of repeating the flights made by the lesser kestrels from their nests to their foraging areas, and three additional flights following random transects over the agricultural fields. Random flights connected locations randomly selected in a straight line. Pictures of the area overflown were taken using the onboard photo camera that was shooting continuously while the aircraft was following the routes.

Data analysis

Given that the accuracy on altitude measurements of the GPS used for navigation is relatively low, to georeference the pictures taken by the camera onboard we used information provided by an Eagletree GPS logger V.4 (Eagletree systems, WA, USA) that includes a barometric altitude sensor. The pictures were georeferenced using a customized extension of ENVI software that used Eagletree data to generate GeoTIFF files.

Images taken from the UAS let us clearly identify six types of field crops (or land uses): harvested cereal, fully grown cereal (unharvested), olive trees, sunflowers, fallow land and ‘others’ (e.g., farm houses, barns, roads, streams). Using ArcGIS v.10 (ESRI, Redlands, CA, USA), we measured the percentage of total distance overflown by the UAS over each field type, as well as the number of field margins crossed by the UAS. To evaluate the capacity of UAS to follow kestrels’ routes, we used the tool ‘NEAR’ implemented in ArcGIS to calculate the distance between each kestrel fix to

the nearest UAS fix. For this analysis, we deleted the part of kestrel tracks related to active hunting activities and distinct from displacement flights between the colony and the actual foraging grounds (easily recognizable by changes in elevation, direction and speed between consecutive fixes at the distal part of tracks; see Figure 1).

Fig. 1. Track of a lesser kestrel foraging flight over the images obtained by an unmanned aerial system. A White and black tracks correspond to unmanned aerial system and lesser kestrel flights, respectively. The circle indicates the hunting area. The rectangle indicates the enlarged area in B. B High resolution images showing sunflowers, olive trees, road and harvested cereal fields.

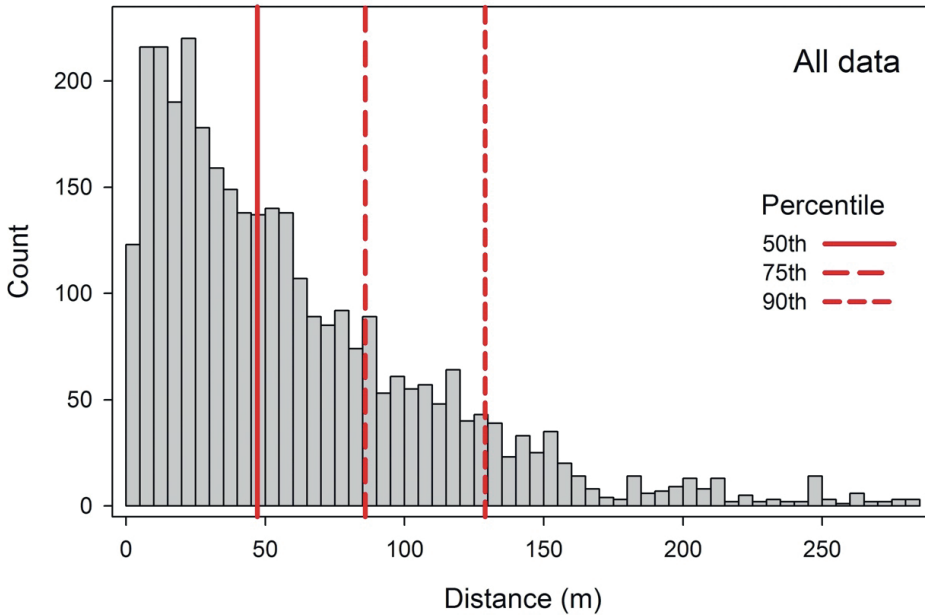


RESULTS

We obtained 4,460 high resolution images along six different flights (three following the kestrels plus three random transects), but there was a high degree of overlap, and we finally selected 466 of them to build the photo-mosaics. The kestrel actual flights recorded by the bird data loggers were always included in the imagery

taken by the UAS (Figure 1). UASs followed the kestrel tracks with high precision, with the majority of recorded distances between kestrel and UAS fixes lower than 50 m. The 75th and 90th percentiles were 85.9 and 128.9 m, respectively (Figure 2). Spatial resolution of imagery depends on the altitude at which images are taken (Figure S3). Our UAS flew at a mean altitude of 184 m, and thus, the mean spatial resolution of imagery was 7.7 cm.

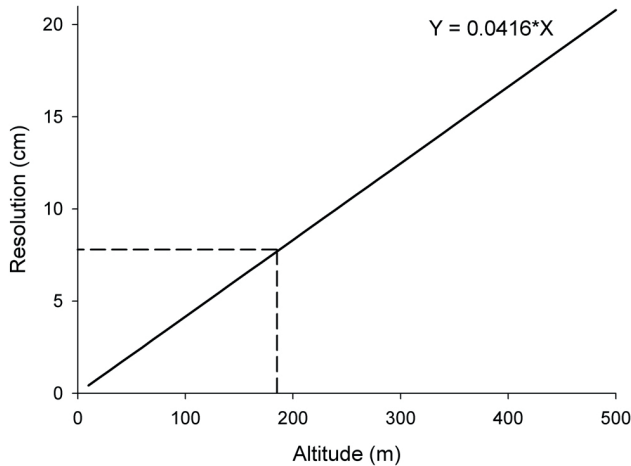
Fig. 2. Distribution of nearest distances between kestrel and UAS fixes. Fixes from each flight are combined. Fixes were taken one per second.



The area overflown by kestrels is intensively cultivated, being divided into small plots of sunflower, cereal (mainly wheat), olive groves, and other minor cultivations. Proportions of overflown field types did not show significant differences between flights (i.e. go, return and random transect flights; Table 1), so that kestrels flew them in proportion to their availability. Additionally, go and return flights did not differ from the random flights performed by the UASs in relation to the proportion of habitat types. This suggests that the kestrels did not follow specific prospecting strategies when getting to the foraging areas or leaving them. However, local

environmental conditions affecting kestrel flight decisions at a microscale, such as wind gusts, could not be recorded in our aerial photographs.

Fig. S3. Relationship between image resolution and altitude. Dashed lines indicate the mean altitude flow (184 m) and the mean spatial resolution of the imagery (7.7 cm).



DISCUSSION

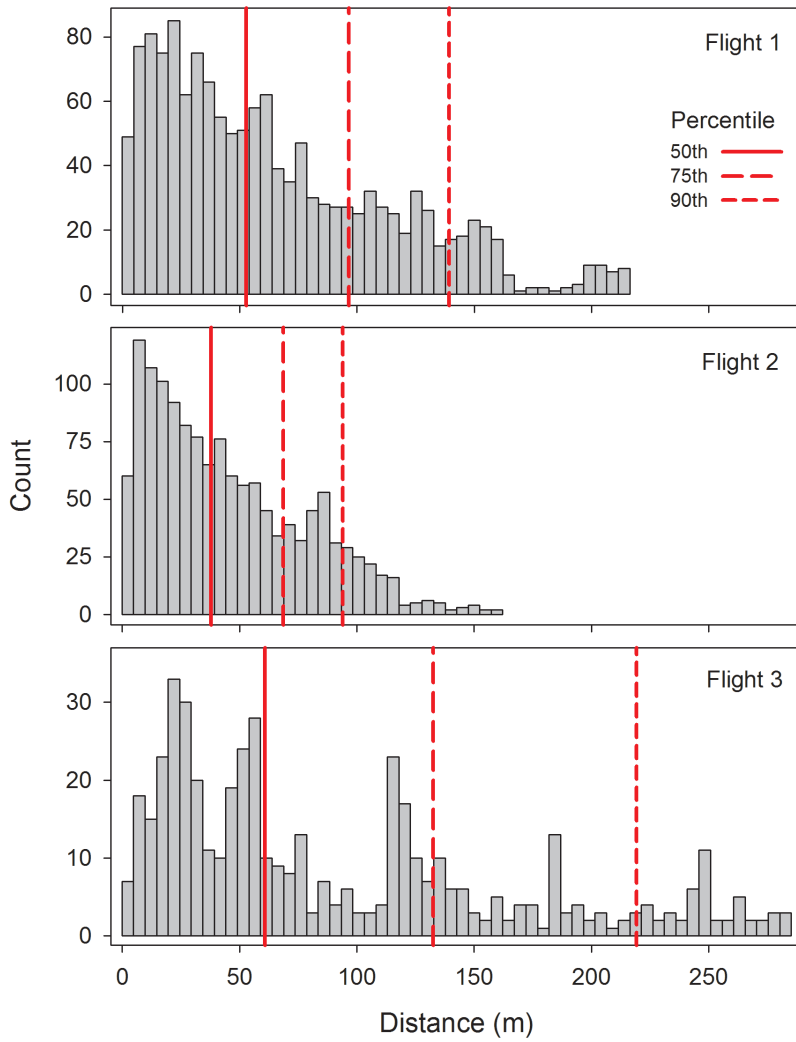
The lesser kestrel is one of the smallest raptors in Eurasia and its size, and particularly body mass, poses a serious limit to the weight of biotelemetry devices or loggers that can be attached (about 5–6 g maximum, depending on the individual) to record spatial position or behavioral activity. During the course of our investigations on the lesser kestrel, that began in 1988 (Negro 1997), we have always pursued to get an accurate knowledge of their daily movements at their breeding grounds. Applying radio transmitters and direct behavioral observations of unmarked individuals we have been able to determine foraging habitat preferences (Donázar *et al.* 1993; Ursua *et al.* 2005; Ribeiro 2007) but soon realized that we lost track of the birds more often than we located them, biasing our studies to locations near the breeding colony. Later on, geolocators have permitted us to determine that kestrels from southern Spain wintered in the Sahel area of western Africa (Rodríguez *et al.* 2009). While this was a breakthrough with conservation implications, due to the low spatial precision of the technology, it was useless to monitor movements at the breeding grounds. It was not

until recently that programmable GPS data loggers small enough to be fitted in a lesser kestrel became available.

This technology has revealed that individual kestrel sometimes forage 15–20 km away in straight line from the breeding colony (data not shown). A question emerged as what type of habitats the kestrels were selecting out of the available ones. Lesser kestrels are colonial birds that exploit sudden outburst of invertebrate prey (Cramp & Simmons 1980). They defend no foraging grounds and flocks of several birds may be sighted hovering and diving at times on ground-based or low flying potential prey (Cramp & Simmons 1980). Although information on crop types may be obtained from satellite images, kestrels are known to respond to rapid structural changes of vegetation in their environment (Ribeiro 2007). A flock of kestrels may hunt on a particular harvested field for one or two days and never be back. Keeping this in mind, we used the UAS, as it could be deployed immediately after we downloaded GPS data from individual kestrels.

The results presented here are meant as a demonstration of the capabilities of the UAS to obtain a mosaic of images corresponding to the actual full foraging trips of free-ranging small birds. The UAS flight paths reproduced the kestrel flights reliably, as indicated by the fact that their trajectories tended to be less than 100 m apart (see Figure 2). The precision fit of the UAS autopilot depends on the number of waypoints included in the settings (note that our Ikarus autopilot admits 32 waypoints), as well as the meteorological conditions, so we foresee precision will be improved using better autopilots. In addition, images taken by the camera installed in the UAS flying at average altitude of 184 m above sea level covered an area on the ground that always contained the bird track projection (Figure S4). Post-processing of the pictures resulted in a mosaic of georeferenced images allowing an evaluation of habitat types as well as plot sizes and other landscape features, such as grassy field margins, roads, power lines, or even the presence of harvesters in the fields (data not shown; but see Figure 1 for examples of field margins and roads). In fact, UAS images taken from a mean altitude of 184 m showed a higher resolution (7.7 cm) than freely available satellite images (e.g. those coming from MODIS, 250 m, or Landsat TM or ETM+, 30 m), under request commercial satellite images (e.g. DigitalGlobe, Colorado, USA, 30–65 cm) or orthophotographies (e.g. Junta de Andalucía, Spain, 1–1.5 m).

Fig. S4. Distribution of nearest distances between kestrel and UAS fixes. Fixes were taken one per second.



To obtain habitat information, there are other alternative (or complementary) options (see Table S2). The most basic would be to get to the study area and survey it by foot or using a ground vehicle. This is time consuming, it has logistical complications and some landscape variables (at large scales) may not be easily quantified. Stationary cameras or sensors scattered in the landscape can provide interesting information about environmental changes, but they involve a huge economic investment and previous knowledge of animal movements, long post-processing of the data, and it is always risky for the equipment, especially in open areas where they can be damaged or stolen. Satellite images are very useful for spatial studies, but their spatial and temporal resolution may not suit research objectives. In our study case, freely available satellite images do not reach the necessary spatial and temporal resolution to distinguish changes in the highly dynamic habitat (e.g. harvested vs. non-harvested fields). For example: NASA's Earth Observing System Data and Information System (EOSDIS) can provide only 250-m resolution images from MODIS sensor twice a day for Spain; but they are affected by clouds and have a spatial resolution too low for our aims. Commercial satellite images with the appropriate spatial resolution could be available, but at a high cost and there is greater delay in data acquisition compared with UAS. Aerial photographs can be ordered from specialized firms, but a mosaic of georeferenced images of the landscape would be quite expensive, and it would be logistically problematic to obtain the pictures when needed, i.e. at the desired temporal resolution.

In the case of small birds, the recreation of flight paths of birds has been achieved using radio-tracking devices and miniaturized video cameras (Rutz *et al.* 2007; Millspaugh *et al.* 2008; Rutz & Bluff 2008; Bluff & Rutz 2008; Sakamoto *et al.* 2009; Grémillet *et al.* 2010). However, if home range is large enough to lose the radio signal or there is no previous information on where the birds are moving, this methodology may bias the results (see Millspaugh *et al.* 2008). In larger birds, cameras have been attached on them (e.g. seabirds Sakamoto *et al.* 2009; Grémillet *et al.* 2010), but in a non-systematic way and with no possibility to get zenithal images of enough high quality that could be processed in a statistical manner. In our case, there is admittedly a delay of several hours between the flight of the bird and that of the UAS, but this is of little relevance for answering most of our ecological questions.

Table S2 Pros and cons of commonly used techniques for recording environmental information. This table is based on our study case, i.e. an actual case to study the habitat selection of Lesser Kestrel using the kestrel flight tracks. Note that advantages/disadvantages may change according to the aims of the studies.

Approach	Advantages	Disadvantages
Survey by foot, on horseback or using a terrestrial vehicle	Low cost of technology	Economic costs per ha can be high depending on technician salaries. Time consuming. Difficulty to Access to some areas (e.g. fences private farms, rugged or remote areas with no paths/roads). Lack of aerial perspective.
UASs images	High resolution (depending on flying altitude). Versatility to record other variables (e.g. by using thermal, infrared or UV light cameras, or even other sensors such as barometers or thermometers). Possibility to simulate the bird field of vision. Quasi-immediate data collection.	Medium economic costs (see Table S1). Range (depending on UAS characteristics). Limited by favorable weather conditions.
Animal borne video	Real time	Device mass is too large to be used in a majority of bird species. Photographed areas are not taken in a systematic way (e.g. No zenithal images)
Commercial satellite images	High resolution (30-65 cm). Versatility to record other variables (e.g. using the 8 band multispectral imagery).	High economic costs. Time lag to set an order (i.e. no immediate data collection)
Medium resolution satellites	Low cost. MODIS and Landsat TM and ETM+ images can be obtained for free.	Low spatial resolution. Optical satellite sensors are limited by clouds, which can limit acquisition of simultaneous images.
Commercial aerial photography taken from conventional aircraft	High resolution (depending on flying altitude)	High economic costs. Time lag to set a order (i.e. no immediate data collection).
Airborne hyper spectral sensors	High spatial and spectral resolution allows measuring a wide range of environmental variables.	Very high economic cost. Limited availability of sensors and operators. Difficulty of organizing an airborne campaign at short notice.

In our study, GPS data for bird positions was obtained at a frequency of one fix-per-second. In the trade-off among fix frequency vs. length of the registration period, we favored the former for improved spatio-temporal accuracy. Our decision rested on two facts: one, this configuration let us to distinguish among soaring, gliding and hunting flights (i.e. hovering and strikes) according to elevation, direction and speed of fixes; and two, the kestrels we were tracking, even if free-ranging, were easily captured in the colony situated on the roof of our headquarters. This condition, the easy of retrieving the GPS data logger to download data, is not met in a majority of investigations on wild birds (Millsbaugh *et al.* 2008). Therefore, future technological advances to finely track a wider range of small sized species should include remote wireless downloading of the GPS information by GSM, Bluetooth or radio. For the moment, this technology has only been incorporated to relatively large devices that can only be mounted on correspondingly large bird species (see www.celltracktech.com, www.technosmart.eu, van Diermen *et al.* 2009).

In addition, UASs can be configured to carry on board additional sensors, such as barometers, thermometers or video cameras. These capabilities of the UAS as a non-intrusive tool for ecological research can also be envisaged as extremely useful in studies of flight dynamics (e.g. recording atmospheric parameters such as temperature, wind direction and strength, or barometric pressure Shepard *et al.* 2011), predator-prey interactions (e.g. recording UV light from prey urine tracks which may attract to predators Viitala *et al.* 1995), social dynamics (e.g. monitoring birds of different species during migration Chabot & Bird 2012) or behavioral decisions related to the conservation of species (e.g. recording what shearwater fledglings would see when they are fatally attracted to artificial lights during their first flights from nest-burrows to sea Rodríguez & Rodríguez 2009; Rodríguez *et al.* 2012b). As a future refinement, UASs may also be used to locate and track at a safe distance animals equipped themselves with radio transmitters or other locating devices. All the heavy equipment, such as video or still cameras, would go in the UAS and the animal would just carry a light weight location device.

Our UAS flew programmed routes, providing georeferenced images of the area overflowed by kestrels. The combination of the GPS position provided by the data loggers and the images provided by the UAS recreate the trajectory of a bird carrying a camera. It improves, however, the performance of the other techniques available to date to study the environment as conventional fieldwork, satellite imagery, aerial pictures or stationary cameras.

ACKNOWLEDGEMENTS

We thank Manuel Baena for fitting a video camera to monitor the nests, Carlos Marfil and Miguel Fernández for their help during the captures of lesser kestrel in the colony, and David Aragonés and Isabel Afán for their advice with GIS work at LAST-EBD. Esteban Guerrero and Miguel Ángel Aguilar, of the Aeromab project team, manned the UAS and prepared the image mosaic. Rafa Silva and Pepe Ojeda built the simulation flight of the kestrel and the UAS. Todd Katzner, Pascual López-López, Katherine Renton and an anonymous reviewer made useful comments on early drafts of this manuscript. We thank Junta de Andalucía and UE for granting the research projects (i.e., AEROMAB, HORUS and PLANET).

SUPPORTING INFORMATION FILES

-Video S1. Simulation of kestrel and Unmanned Aerial System (UAS) flight paths.

"That is the problem with the government these days. They want to do things all the time; that is not what people want. People want to be left alone to look after their cattle". Alexander McCall Smith

Chapter 4: Conservation in a protected area



[This Chapter is submitted as: Mulero-Pázmány, M., Barasona, J.A., Vicente, J., Negro, J.J. Could Unmanned Aerial Systems constitute an alternative to bio-logging for animal spatial ecology studies?]

ABSTRACT

The knowledge about the spatial ecology and distribution of organisms is important for both basic and applied science. Bio-logging is one of the most popular methods for obtaining information about spatial distribution of animals, but requires capturing the animals and is often limited by costs and data retrieval. Unmanned Aerial Systems (UAS) have proven their efficacy for wildlife surveillance and habitat monitoring, but their potential contribution to the prediction of animal distribution patterns and abundance has not been thoroughly evaluated.

In this study, we assess the usefulness of UAS overflights to: i) get data to model the distribution of free-ranging cattle for a comparison with results obtained from GPS-GSM collared cattle, and ii) predict species densities for a comparison with actual density in Doñana Biological Reserve (South of Spain). UAS and GPS-GSM derived data models provided similar distribution patterns. Predictions from the UAS model overestimated cattle densities, which may be associated to higher aggregated distribution of this species.

Overall, while the particular researcher interests and species characteristics will influence the method of choice for each study, we demonstrate here that UAS constitute a non-invasive methodology able to provide accurate spatial data useful for ecological research, wildlife management and rangeland planning.

Keywords: *Unmanned Aerial Systems UAS, drones, bio-logging, GPS-GSM collars, cattle, animal monitoring, abundance modeling, spatial distribution, Remote Piloted Aircraft Systems (RPAS).*

INTRODUCTION

Assessing the distribution of animal species among available environments and the reasons behind those patterns are recurrent ecological questions that may also affect human activities and conservation efforts (Morrison *et al.* 2006). Resource utilization, wildlife management, conservation planning, ecological restoration and prediction of possible future impacts of land use or climate changes are all applied areas that benefit from spatial distribution models of individuals, populations, species and communities (Collinge 2010; Qamar *et al.* 2011).

Numerous methodologies are available to collect spatial data for animals. Direct methods include observation, capture, biotelemetry, radar, laser and cameras, whereas indirect methods are dependent on some evidence of animal activity in an area or specific site (e.g. bed sites, faeces, nests or tracks) (McDonald *et al.* 2012). Bio-logging consists in the remote data collection from free-ranging animals using attached electronic devices (Cooke *et al.* 2004). This is an increasingly popular option among ecologists because it provides valuable information on the animals' movements and habitat use. This method has experienced a remarkable development thanks to the continuous technological advances, especially those regarding tags miniaturization in recent years. Nevertheless, bio-logging techniques present some constraints, including logistical challenges, possible undesirable effects on the animals during the capture, handling and along the period on which the individuals are tagged (see Murray & Fuller 2000 for a review) and the limitation in the number of animals that can be studied, constrained by the number of tags deployed, which are often expensive (Rutz & Hays 2009).

Reliable estimates for species abundance at large spatial scales are highly demanded in order to establish bases on which management schemes can be sustained. It is well known that wildlife population abundance is not easily estimated and a plethora of methods have been described for this purpose in the scientific literature (e.g. Morellet *et al.* 2010). For a given species, the effort required to apply each method is highly variable and it determines their applicability to be used, mainly at large spatial scales. Obviously, the efforts required to determine the abundance of a species at large spatio-temporal scales exclusively from fieldwork are unworkable for most of the studies. Thus, surveying a number of representative populations, on which the relationships between species abundance and the environmental conditions can be determined, is a way to forecast the abundance in unsampled territories, by generalizing the adjusted species abundance–environmental gradients relationships

(e.g. Etherington *et al.* 2009; Acevedo *et al.* 2014). In this regard, to record reliable information of species abundance is one of the challenges for wildlife management.

Unmanned Aerial Systems (UAS hereinafter) have proven useful to address various ecological challenges involving animal monitoring (Jones 2003; Watts *et al.* 2010; Sardà-Palomera *et al.* 2012; Vermeulen *et al.* 2013) and habitat characterization (Koh & Wich 2012; Getzin *et al.* 2012). The potential value of UAS for spatial ecology is enormous (Anderson & Gaston 2013) but to date, there are just a few studies that have explored their possibilities (Rodríguez *et al.* 2012a; Chabot *et al.* 2014).

The aims of this work are to test the suitability of aerial images obtained from UAS flights for i) modeling spatial distribution patterns of animals as compared against a widely used method (bio-logging using GPS-GSM collars), and ii) predicting species abundance by comparing estimates from the images with actual abundance in the study area. We use as model species free cattle *Bos taurus* inhabiting Doñana Nature Reserve (Southwest of Spain) under a traditional husbandry system. Cattle are large mammals that offer logistical advantages for bio-logging deployment, are easily detectable in UAS images and precise abundance data are available. In addition, the knowledge of the spatial distribution of these large herbivores is critical for ecosystem management (Lazo 1995; Bailey *et al.* 1996). Researchers and park managers are specially interested because cattle presence and their foraging impact in the protected area is a controversial issue (Espacio Natural Doñana 2000). Health issues are also at stake, as cattle share habitat, resources and diseases such as tuberculosis with wild ungulates (see Gortázar *et al.* 2008).

MATERIAL AND METHODS

Study site and species

Doñana Nature Reserve (DNR hereinafter, 37°0' N, 6°30' W) is located in the right bank of the Guadalquivir river estuary in the Atlantic Coast (Andalusia, Southwest of Spain). DNR covers 1,008 km² and hosts a unique biodiversity and ecosystems including marshlands, lagoons, scrub woodland, forests and sand dunes that led to its declaration as a World Heritage Site and Biosphere Reserve (UNESCO 2014). The area has a Mediterranean climate classified as dry sub-humid with marked seasons. We performed the field work during the dry season, when the study area includes the following main habitats: (LT1) dense scrub dominated by *Erica scoparia* and *Pistacia lentiscus*, (LT2) low-clear shrubland, mainly of *Halimium halimifolium*, *Ulex*

minor and *Ulex australis* (LT3) herbaceous grassland, (LT4) *Eucaliptus sp.* and *Pinus sp.* woodlands, (LT5) bare lands, sandy dunes and beaches, (LT6) water bodies and vegetation associated with watercourses covered mainly by *Juncus sp.* patches (Fig 1). A north-south oriented longitudinal humid ecotone can be identified between the scrublands and the edge of the dry marshlands, dominated by *Scirpus maritimus* and *Galio palustris* with *Juncus maritimus* associations. The study area in DNR is divided in four Management Areas (MAs hereinafter) from South to North named respectively: Marismillas (MA1), Puntal (MA2), Biological Reserve (MA3), and Sotos (MA4).

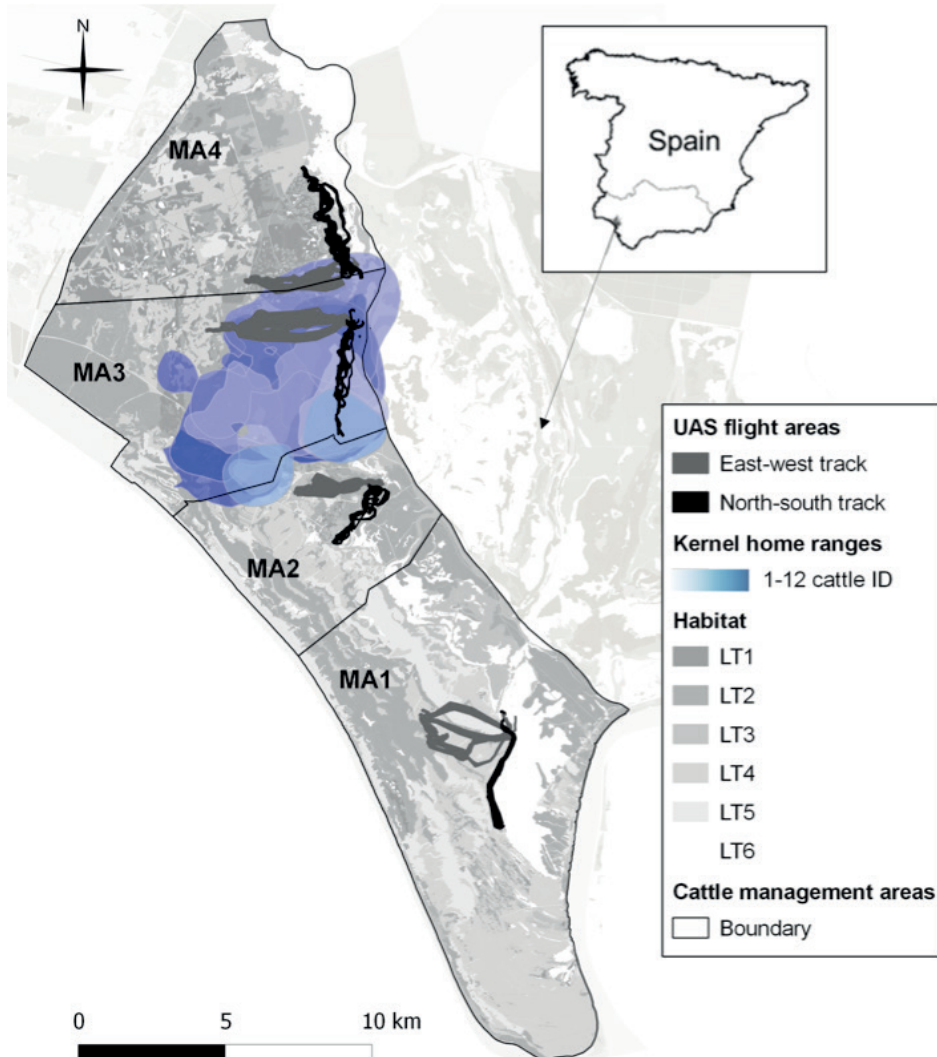
Our model species is free-ranging cattle *Bos taurus* that occupy different MAs and are captured just once per year for sanitary handling. Since 2000, cattle are managed according to the Cattle Use Plan (Espacio Natural Doñana 2000) which determines the number of individuals allowed on each MA (MA 1=318, MA 2=152, MA 3=168, MA 4=350). Doñana cattle is an autochthonous breed, named Mostrenca, although some cross-breeds exist in some herds.

Unmanned Aerial Systems (UAS) methodology

We completed a total of 192 km of UAS diurnal aerial tracks of two types (east-west and north-south oriented transects) on each cattle management area with six replicates (Fig 1). UAS surveys took place during August and September 2011, the end of the dry season and a time when food resources become more limiting for herbivores in DNR in terms of water and forage availability (see Bugalho & Milne 2003) between 3 p.m. and 8 p.m. (local time). The tracks were performed at an average speed of 40 km/h at 100 m altitude above ground level. The covered strips were approximately 4 km long and 100 m wide (Fig 1).

The flights were performed with a small UAS (1.96 m wingspan; see Fig 2) assembled at Doñana Biological Station using a foam fuselage of an Easy Fly plane (St-models, China) propelled by an electrical engine. It is equipped with an Ikarus autopilot (Electronica RC, Spain), which provides waypoint following capability and an Eagletree GPS logger V.4 (Eagletree systems, WA, USA) with a barometric altitude sensor. The digital photo camera Panasonic Lumix LX-3 11MP (Osaka, Japan) is integrated in the plane wing nadir pointing and the shutter is activated by a mechanical servo. The images were taken in speed priority mode and in its widest zoom position with continuous shooting. Total price of the system was around 5,700 € as of June 2012.

Fig. 1. Map of DNR study area. Habitat is mainly divided in dense scrub (land cover type, LT1), low-clear shrub land (LT2), herbaceous grassland (LT3), woodland (LT4), bare land (LT5), watercourse vegetation and water body (LT6). UAS tracks at the 4 cattle management areas and Fixed Kernel (95% Utilization Distribution) home ranges of GPS collar locations at Biological Reserve (MA3) are represented.



We geo-referenced the images using the information provided by the UAS with a customized extension of ENVI software using Eagletree data to produce GeoTIFF files. Accuracy of our UAS locations is estimated in the range of 10-50 m (Mulero-Pázmány *et al.* 2014, authors' unpublished data) before post-processing, and was improved up to 1-3 m after GIS corrections (superimposing the image on orthophotos and manually correcting it by using reference points). We traced the animals in the images and processed them over a 1 ha approximated patch size (grid) as proposed in detailed studies on ungulate behavior (Gibson & Guinness 1980).

GPS-GSM methodology

Twelve Mostrenca breed cattle were equipped with GPS-GSM collars along July 2011 in the Biological Reserve (MA3) (Fig 2), during routine veterinary inspections with the animals restrained in a cattle chute. The collars included a satellite position capture system (GPS) and a Global System for Mobile communications (GSM) (Microsensory System, Spain) (Cano *et al.* 2007). The price per collar is 2,750€ plus sms service, covered by the manufacturers in our case. The collars were programmed to take a GPS location every hour, sending encoded packs with 20 positions to the central station when mobile phone coverage allowed. Data collected included date, time, geographic coordinates and Location Acquisition Time (LAT hereinafter, precision measure to obtain a fix; range from 0 to 160 sec). We screened our data using $LAT \geq 154$ sec to detect anomalous fixes (manufacturer's technical data; Microsensory System, Spain). We obtained a fix-rate of 93.95%, which is acceptable considering that fix rate success of $< 90\%$ can cause habitat-induced bias in resource selection studies (Frair *et al.* 2004). Positional error associated with GPS locations was 26.64 m on average, SD= 23.5 m, according to stationary tests carried out in the center of our study area.

Fig. 2. Left: UAS. Mostrenca cattle equipped with GPS-GSM collar. Right: image obtained with UAS of Mostrenca cattle aggregated in the ecotone of the study area.



Data analysis

Landscape covariates

Environmental variables were estimated from thematic cartography 1:10,000 scale (Consejería de Medio Ambiente y Ordenación del Territorio. 2013) using Quantum GIS version 1.8.0 Lisboa (QGIS Development Team 2012) and were determined following the information of the factors potentially regulating ungulates spatial abundance in the study area (Braza & Alvarez 1987). For each 1 ha grid of the study area (total = 29,532 grids, including the 10.1% corresponding to UAS track grids; $n=2,983$) and for each 26 m radius buffer (according to GPS positional error) around each GPS cattle (used) and random (available) locations (Jerde & Visscher 2005), we calculated: distance to nearest artificial water hole (DW); distance to nearest marsh-shrub ecotone (DE); exact grid area (GA) to control the variation in UAS image areas in the case of UAS track grids, and proportion of the different land cover types (LT1-LT6). Distances, areas and land cover type proportions were treated as continuous variables (Table S1) and cattle management area (MA) as a categorical variable. Distance variables were obtained as the shortest distance from each grid and buffer centroid to the nearest environmental feature.

To correct visibility reduction produced by vegetation cover for cattle detection in UAS images, we calculated detection coefficients for LT1 and LT4 land cover types. We estimated the detection proportion of 100 random circle points (1 m² size) created in QGIS from ten different habitat images (1 ha) of each cattle management area and land cover type (80 images analyzed). Detection coefficients used in statistical analysis were 0.544 for LT1, and 0.360 for LT4, respectively. Colinearity between explanatory variables was tested with Spearman's pairwise correlation coefficients $r > |0.5|$ (Hosmer & Lemeshow 2000).

Cattle distribution modeling

We tested the factors affecting the spatial distribution of cattle by (i) using UAS images as a first approach; and (ii) using GPS-GSM collar locations as a second approach, by means of Generalized Linear Models (GLM).

For the UAS model, we only included the east-west UAS track data, because north-south UAS tracks showed low habitat feature variation (these data were later used for model validation). The response variable was the number of detected animals per UAS grid and was modeled with a negative binomial distribution and logarithmic link function. The final UAS model was obtained using a backward stepwise procedure based on the Akaike's information criterion (AIC) (Akaike 1974).

For the GPS model, we used Resource Selection Function (RSF) logistic regression (Manly 2002) where used locations (only considering the ones obtained during the same period-hours of UAS flights) were coded as 1, and random locations (available, ten per used GPS location), inside the individual Fixed Kernel (95% utilization distribution) home ranges, as 0. The response variable is presence/absence of cattle in the grid, and the model included the variables selected for UAS approach except the MA categorical factor (since the collared animals were restricted in MA3).

Validation and comparison between the two methods

UAS model validation was performed by mean of Pearson' correlations with independent (20%) data of the east-west tracks and all information in north-south UAS track dataset. GPS model validation was performed by assessing the predictive capacity of each model with the area under a relative operating characteristic (ROC) curve (AUC), to rate the probability that the models correctly discriminated between used and random locations. The AUC ranges from 0.5 for models with no

discrimination ability to 1 for models with perfect discrimination (Pearce & Ferrier 2000).

Spatial predictions of both final models were transferred to MA3 area where visual and quantitative comparisons were conducted to verify correspondence between predictions of UAS and GPS approaches by Spearman's pairwise correlation. All statistics were performed in R version 3.0.1 (R Foundation for Statistical Computing, Vienna 2013).

We also compared the densities (number of animals / surface) predicted by the UAS model with the current density in the different MAs (data provided by Doñana Biological Reserve and Doñana National Park authorities) evaluating cattle aggregation in the grids by variance to mean ratio (Elliot 1977).

RESULTS

A total of 358 individual cattle were identified and located on the UAS track images along DNR (Fig 2). We did not observe any disturbance reactions to the UAS during the overflights from the cattle nor from other ungulates present in the area. Overall, the GPS collars fixed 1,752 locations of the 12 marked animals during the same period of UAS flights. Table S1 illustrates the descriptive statistics for the analyzed continuous landscape covariates in the UAS track grids, GPS (used and available) location buffers and total MA3 and DNR grids.

Results of the variables included in the spatial distribution models selected by the stepwise procedure (ΔAIC), estimated coefficients, standard errors and significance are summarized in Table 1 for each approach. The best UAS fitting model ($AIC = 397$, ΔAIC from saturated model = -32) found that the environmental covariates influencing cattle distribution are mainly related to landcover types, with a positive effect of grasslands on the ungulates distribution and a negative effect of the distance to the ecotone and to shrubs. UAS best fitting model also revealed a significant effect of the management area on cattle abundance. GPS method identified all the included variables as significant and showed the same effect of them over cattle presence.

Table 1. Results of Generalized Lineal Model approaches (best fitting model for UAS dataset and a model for GPS location dataset with UAS selected covariates). Statistical parameters (Estimate Coefficient and Standard Error SE) are shown for the models.

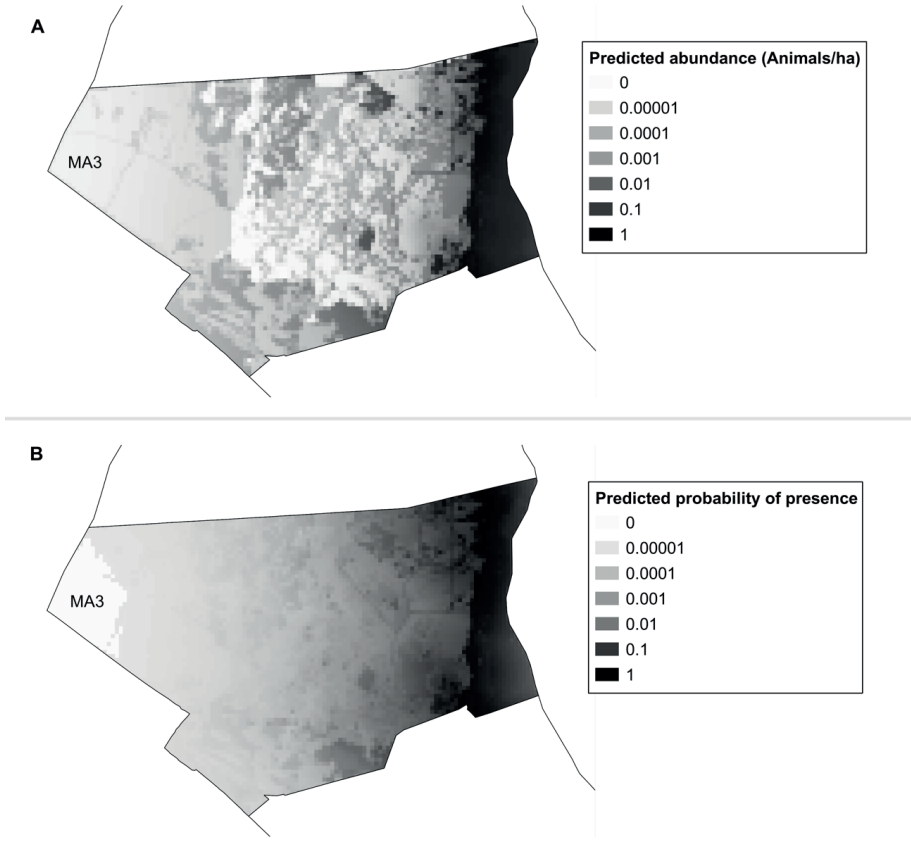
		Coefficient (SE)	
		UAS method	GPS method
Intercept		-2.6910 (0.7280)***	-0.0820 (0.0610)
Variables			
DE	Distance to nearest marsh-shrub ecotone (km)	-0.0006 (0.0004)*	-0.0028 (0.0001)***
LT1	Dense scrub (%)	-13.270 (4.3270)**	-0.0206 (0.0011)***
LT2	Low-clear shrub (%)	-2.0360 (0.86189)*	-0.0316 (0.0013)***
LT3	Herbaceous grassland (%)	2.3320 (0.6438)**	0.0044 (0.0007)***
MA1	Management area (1)	Ref. category	
MA2	Management area (2)	2.8060 (0.7901)***	
MA3	Management area (3)	1.8070 (0.8591)*	
MA4	Management area (4)	2.2570 (0.9636)*	

P values: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Validation of the model predictive performance on independent UAS track datasets showed that the selected best spatial distribution model performed adequately with significant Pearson's rank correlations (east-west data: $r = 0.30$, $p < 0.001$, $n = 258$; and north-south data: $r = 0.32$, $p < 0.001$, $n = 852$). The assessment performed for the GPS location model showed a high predictive capacity (AUC = 0.945). These validation results permitted the transference of the models to the MA3 by using total 1 ha grids (Fig 3).

The map representing predicted spatial distribution of cattle shows common distribution patterns throughout MA3 between UAS and GPS approaches. High relations were found between the predicted values of UAS and GPS methods in the MA3 by Spearman's rank correlation: $r = 0.716$, $p < 0.001$, $n=6,501$.

Fig. 3. Map of DBR study area (MA3) with the transference at 1 ha spatial resolution of the cattle predicted spatial distribution values obtained by modeling landscape variables with: A) UAS model (predicted abundance of animals); and B) GPS model (predicted probability of presence).



The mean of predicted densities calculated by the UAS approach for each MA were higher than the densities provided by DNR authorities, showing differences between the four MA of DNR, with more overestimated values in the MA with higher aggregation coefficients (Table 2).

Table 2. Cattle density (individuals/ha) provided by DNR authorities, (actual), UAS predicted density and variance to mean ratio as an aggregation indicator.

Management area	Actual density	UAS Predicted density	Predicted to actual density ratio	Variance to mean ratio
1	0.031	0.035 ± 0.030	1.13	1.77
2	0.040	0.118 ± 0.124	2.95	19.82
3	0.026	0.033 ± 0.084	1.27	2.79
4	0.057	0.139 ± 0.196	2.44	15.84

DISCUSSION

In an effort to assess the ability of UAS to contribute to animal spatial ecology studies, we compared the predicted spatial patterns of free-ranging cattle in Doñana Biological Reserve obtained by using animal locations from UAS overflights images against locations from bio-logged cattle (GPS-GSM collars). Both models, using the same environmental covariates, performed well and provided similar spatial distributions of cattle at a very fine scale (1 ha grids).

Models results

The environmental variables selected by the UAS model to explain the abundance of cattle are those expected to be more important from an ecological perspective. The positive influence of herbaceous grasslands on ungulates distribution reflected by our models has been previously identified by other authors (Bailey *et al.* 1996) indicating the need to forage on green pastures during the dry season. The ecotone between the shrublands and the marshlands is the richest area of DNR, keeping a higher soil humidity than other areas and offering not only grasslands but also tree shade and refuge which are valuable for ungulates in the dry season (see Braza & Alvarez 1987). Models also showed a negative effect of dense and low-clear shrub on cattle presence, that tend to avoid those land types in favor of the open grassland areas (Casasús *et al.* 2012). However, this work is limited to data obtained at a specific time of the day, as our main goal is to compare two methods in the same conditions, and therefore general habitat use by cattle should be addressed in a more complete study performed all day round.

Although the UAS method worked successfully for predicting cattle spatial patterns, it overestimated cattle density in all the management areas (Table 2). This discrepancy may be explained because the flight locations were biased towards the areas where cattle is more concentrated, a problem which could be solved by performing stratified surveys in the different habitats. Also, the overestimation is not homogeneous along DNR, but higher in those areas with a more aggregated distribution. This fact has been proven relevant for animal surveys in general and manned aerial censuses -more related with UAS- in particular (Tellería 1986; Fleming & Tracey 2008). There are various protocols to assess this effect (Redfern *et al.* 2002; Tracey *et al.* 2008) and techniques to correct it (Bayliss & Yeomans 1989; Fleming & Tracey 2008) that should be considered if the researcher main objective was estimating abundance, for instance increasing sampling effort as cattle spatial aggregation does.

Methods comparison

Although bio-logging and UAS approaches proved to be useful in our study, there are several factors that condition their general applicability in spatial ecology. On the basis that the most desirable aspects for carrying out spatial ecology studies are to optimize sampling size and data accuracy, but maximizing diversity and frequency for both the animals and the habitat while minimizing impact, cost, logistic and data processing effort, we provide below an analysis of the pros and cons of each method.

Sampling size

Sampling size for bio-logging is limited by financial constraints and/or trapping success (Cooke *et al.* 2004; Rutz & Hays 2009). This may lead to incurring in data biases caused by the selection of animals to be fitted with tags, including that produced by the non-random selection in relation to age, sex and geographic location, which increases if the trapping method is not selective. Deployed tags can fail because they may stop sending data or becoming lost, further reducing sample size, a fact that may lead to biased inferences by focusing on the space use of a few individuals while ignoring the position of non-tagged animals (con- or heterospecifics).

Sampling size for UAS monitoring depends on the area the system is able to cover during the flights (which depends on its range and autonomy) and their detection capacity. Fleming & Tracey (2008) analyzed efficacy of manned aerial surveys, also applicable to UAS, identifying the size, shape, color, shadow and contrast against background of the animals, as well as their response to the aircraft as

relevant factors for detection. UAS flight altitude must be a compromise between obtaining adequate resolution to distinguish the species under investigation and the size of the area to cover. Cattle and other smaller ungulate species were easily spotted in our images obtained with an embarked 11 MP commercial camera at 100 m altitude above ground level, in contrast with other studies (Vermeulen *et al.* 2013), where animals smaller than elephants could not be easily identified while flying with a 10 MP camera at the same altitude, maybe because they just made a rapid naked-eye image analysis.

Species behavior and habitat characteristics also affect detectability by means of UAS. Bayliss & Yeomans (1989) noted that the main source of aerial survey bias of feral livestock is obstructive vegetation cover. We addressed this problem in our study by using correction visibility factors adequate for the present land covers. This factor, estimated from random location of points, assumes that animals are also randomly distributed with respect to tree cover, but if the animals were actively seeking tree cover (e.g., if they were looking for shade in hot days), then the UAS density estimates could be underestimated, or just the opposite if individuals selected otherwise. Besides, selection for cover may vary among species, season and time of day (in our case all the flights were performed in the late afternoon and in summer). Equipping UAS with thermal cameras allows distinguishing animals in dense vegetation areas or at night, but it has been proven that detectability with thermal cameras is low for daylight conditions and in dense vegetation habitats (Mulero-Pázmány *et al.* 2014b). Admittedly, behavioral responses and habitat characteristics are less critical when data are obtained through bio-logging. Assuming a suitable detection rate for UAS, one of the main advantages of this method versus bio-logging is that it provides the researcher with an image of the animals that are present in the area, permitting to include group influence or interspecific aggregation as variables of the ecological studies.

Data accuracy, diversity and frequency

Spatial accuracy of the animal locations obtained by UAS after processing is estimated between 1-3 m. This constitutes a major advantage for UAS in spatial distribution studies against bio-logging that provides less accuracy (e.g. 26 m for the GPS collars we used).

The use of specific sensors in bio-logging tags is developing fast, allowing to measure individual parameters (e.g. physiological, behavioral, movement speed and range), which is information that could not be obtained with the UAS approach. On the other hand, UAS have the capacity to provide real time information on habitat

characteristics, which is especially interesting in highly dynamic landscapes (Rodríguez *et al.* 2012a), where short term changes affecting animals' movements (i.e. produced by fires, human interventions, flooding) may not be reflected on satellite or GIS resources available with proper spatial-temporal resolution. This temporal accuracy is important, as obtaining animal information and environmental variables at the same level of detail and reliability would significantly improve ecology studies (Gaillard *et al.* 2010).

While trapping animals may be complex, once the animals are bio-logged they produce enormous volumes of data for a long period of time. Long-term data with UAS requires additional flight field campaigns and it is difficult to associate data to specific individuals. UAS flights are subjected to favorable meteorological conditions that also constraint the period on which data collection is possible.

Impact

Bio-logging requires capture and handling of the animals that, besides involving bioethical approval, might affect their behavior and survival (Silvy *et al.* 2012) thus complicating the use of bio-logging (Cooke *et al.* 2004). A point in favor of the use of UAS is their low impact on the surveyed animals. Due to the small size and the reduced noise UAS produce, animal response is very low (at least not visually noticeable in our case) so that the method does not disturb the study subjects. Electric UAS are also zero-emission vehicles and this is an aspect particularly important when surveying nature reserves. Additionally, because UAS are classified as a non-invasive technique, no approval by Animal Committees is deemed necessary, but legal constraints may affect their use in countries with strict aerial regulations that can prevent the use of this approach.

Cost, logistics and data processing effort

We invested 33,000 € in the 12 collars attached to cattle used for this study. In contrast, the complete UAS system we used had a cost of 5,700 € and it was used in hundreds of flights. As a reference, using data from the same time period in our study for both methods, we obtained single locations of 358 cattle with UAS flights (2,615 ungulates located in total considering horses, red and fallow deer and wild boar), versus the 1,752 locations of 12 individuals that were marked with radio-collars.

Data retrieval is simple for GPS-GSM bio-logging, as the researcher receives animal locations at the office (after the necessary effort of marking the animals), but the UAS method requires images post-processing (georeferencing and detecting the animals in the images) which in our case took about 40 hours of work.

In summary, our results demonstrate that UAS constitute an effective tool for spatial ecology by providing the data required to develop distribution models for at least large animals, which may be comparable to those obtained using other widely accepted techniques such as bio-logging. Different methodologies have their own strengths and weaknesses, and UAS can be a complementary method to broaden objectives in animal spatial studies or to include more spatially and/or socially representative samples. For instance, UAS could be used to obtain a first general picture of a species spatial distribution and abundance patterns that could later be used to select the areas and/or individuals more adequate to be captured for bio-logging. Additionally, information of intra and inter-species interactions for larger groups obtained by UAS could be combined with fine detailed habitat selection data obtained from fewer bio-tagged individuals (or obtained with other methods).

MANAGEMENT IMPLICATIONS

The cattle predictive models obtained in this study contribute to a better understanding of the free-grazing herbivore distribution patterns within a protected area, which is critical for ecosystem management (Bailey *et al.* 1996) because these species have spatially variable impacts on resources (Gordon 1995). Individual or groups contact patterns at intra or inter specific levels, and the study of interactions with habitat features (e. g. environmental aggregation points such as water points) is also crucial for evaluating the epidemiology of diseases in the wild, for which UAS provided excellent information. The methodology developed for this study is not only useful for ecology, wildlife and epidemiology research, but also for rangeland managers who need livestock accurate information for designing effective strategies to optimize their resources (Coulombe *et al.* 2006).

ACKNOWLEDGEMENTS

This study was conducted within the Aeromab Project (Andalusia Government, Project for Excellence, 2007, P07-RNM-03246) and the PLANET Project (European Commission 7th FP Grant Agreement No. 257649). The present work also benefited from the financial aid of the research grants JCCM ref. PEII10-0262-7673 and Ministerio de Ciencia e Innovación ref. AGL2013-48523-C3-1-R. J.A. Barasona received funding from the Spanish Ministerio de Economía y Competitividad (MINECO) and JCCM. P. Acevedo is supported by MINECO and Universidad de Castilla-La Mancha (UCLM) through a ‘Ramón y Cajal’ contract (RYC-2012-11970).

We thank Esteban Guerrero and Miguel Ángel Aguilar, pilots and technicians that operated the UAS and processed the images. Additionally, we wish to thank Manuela González-Suárez for her reviews and for providing valuable comments on this manuscript and Ramón Soriguer, who provided some of the GPS-GSM collars.

SUPPLEMENTARY MATERIAL

Table S1. Environmental covariates, descriptions, mean values (X) and standard deviations (SD) of UAS track grids and GPS locations buffers versus MA3 and total study area grids used in the analysis of cattle spatial abundance patterns in Doñana Nature Reserve (DNR).

Code	Variable	UAS grid (X $\pm$ SD)	GPS location buffer used and available (X $\pm$ SD)	Total MA3 (X $\pm$ SD)	Total study area (X $\pm$ SD)
DW	Distance to nearest water point (km)	0.33 $\pm$ 0.19	0.55 $\pm$ 0.38	0.94 $\pm$ 0.79	0.97 $\pm$ 0.73
DE	Distance to nearest marsh-shrub ecotone (km)	1.22 $\pm$ 0.90	1.50 $\pm$ 1.49	4.06 $\pm$ 2.76	2.47 $\pm$ 2.17
GA	Exacted UAS grid area (ha)	1.25 $\pm$ 0.85	21 $\pm$ 0	1 $\pm$ 0	1 $\pm$ 0
LT1	Dense scrub (%)	24.66 $\pm$ 35.20	20.95 $\pm$ 36.1	18.50 $\pm$ 31.54	11.09 $\pm$ 26.28
LT2	Low-clear shrub (%)	27.54 $\pm$ 34.37	31.14 $\pm$ 42.15	48.59 $\pm$ 41.54	32.04 $\pm$ 39.89
LT3	Herbaceous grassland (%)	14.25 $\pm$ 26.79	28.67 $\pm$ 40.94	10.92 $\pm$ 26.23	12.34 $\pm$ 26.82
LT4	Woodland (%)	18.40 $\pm$ 34.24	4.16 $\pm$ 18.27	11.14 $\pm$ 26.28	19.84 $\pm$ 34.77
LT5	Bare land (%)	8.82 $\pm$ 24.41	2.55 $\pm$ 12.93	4.58 $\pm$ 15.71	11.30 $\pm$ 26.88
LT6	Watercourse vegetation (%)	6.33 $\pm$ 19.95	12.28 $\pm$ 30.03	4.50 $\pm$ 17.61	11.28 $\pm$ 28.24
MA	Cattle management area (categorical 1-5)	-	-	-	-

General discussion

The recent remarkable development of UAS has led to a decrease in prices and a large variety of equipment in the market, which has favored the incorporation of these systems to environmental research. The novelty of the technology explains that there is almost no scientific literature up to only ten years ago, but the explosion of published papers and news in the last three years confirms that the use of UAS is being explored by numerous research teams worldwide.

This Ph.D. thesis attempts to fill the gap of knowledge in the use of UAS in conservation biology. It describes for the first time the use of these systems in an immediately applicable way in impact assessment of infrastructures for wildlife and protection of endangered species. Furthermore, it presents UAS as a tool for obtaining high-resolution spatiotemporal images which help to understand habitat use in rapidly changing human dominated areas and demonstrates that these systems can provide information as valid as the obtained by conventional techniques on the spatial distribution of species in protected areas.

What do UAS bring in conservation biology?

Aerial perspective offered by UAS offers certain advantages over data collection observers from the ground (as far as targets are detectable by the systems) as it allows covering larger areas, saving time and effort on tasks that can be tedious by other means. Even low cost UAS equipped with a basic payload have proved useful for common missions such as power lines characterization (Chapter 1) where the savings in logistics may allow diverting resources towards the installation of mitigation measures, which is ultimately the goal of the impact assessment study. In this line, UAS can also contribute to the impact assessment of other infrastructures that present problems in terms of conservation, such as roads, water channels or wind farms (Crockford 1992; Forman & Alexander 1998; Kingsford 2000). Aerial perspective is convenient for monitoring their surroundings, facilitating the location of death records, mapping the distribution of wildlife and vegetation gradients or controlling the appearance of invasive species that use infrastructures to expand, all constituting useful information for conservation and management.

The most interesting UAS capability for environmental applications is the high spatial resolution information they can provide by means of the embarked sensors (Jones *et al.* 2006; Anderson & Gaston 2013). Although spatial resolution depends on the quality of onboard sensors and flight height, UAS equipped with affordable commercial cameras flying at 100-300 m above ground level, already offer sufficient quality to locate animals (chapter 2, Watts *et al.* 2010; Israel 2011; Sardà-Palomera *et al.* 2012; Vermeulen *et al.* 2013) and to perform habitat characterization (Chapter 3 and 4, Koh and Wich 2012; Getzin *et al.* 2012; Chabot *et al.* 2014) with a resolution of centimeters, much higher and at a lower cost than the achievable with other available technologies (satellite, manned aircraft). In chapter 4 we demonstrate that using UAS it is possible to develop animal distribution models that show similar spatial patterns than those obtained with conventional techniques. Therefore, if the species is detectable, UAS may constitute an alternative to more invasive or expensive procedures (i.e. biologgging, manned flights). Besides, working at a high resolution scale offers to the researcher the possibility of: i) gathering information from all the detectable animals in the surveyed areas, allowing to study inter-individual or interspecific relations, and ii) studying animals distribution in relation to the environment characteristics, which are recurrent ecological questions that may also affect human activities and conservation efforts (Morrison *et al.* 2006).

Small UAS deployment is generally fast, a fact that offers the possibility of obtaining high temporal accuracy data of animals and environmental variables, which can significantly improve ecology studies (Gaillard *et al.* 2010). Microelectronics revolution has allowed gathering high accuracy and high frequency animals position data, but monitoring the environment in which they move with the desired frequency is difficult or expensive (or even not possible) with conventional technology. This is particularly relevant when the environment changes rapidly, especially if the changes that occur affect short-term movements of the studied species, as demonstrated in chapter 3, which may be applicable to other situations (i.e. human interventions, fires, floods). Moreover, thanks to their easy deploy and to autopilots capability, UAS flights are easily repeatable allowing to revisit sites to perform systematic studies (Watts *et al.* 2008; Anderson & Gaston 2013). The contribution of UAS in this aspect looks promising, as they can help to understand habitat selection at a fine scale and improve movement ecology studies.

Most small electric UAS such as the ones used in the majority of environmental research produce reduced noise and are visually discrete. We did not record any negative reactions of the fauna during the performed flights (nor are mentioned in the scientific literature), which in combination with being zero-emission

make UAS a low impact method. This constitutes a major advantage for their use in fauna surveys, as a basic principle of any researcher is not to interfere in the object of study, especially if working with endangered species (chapter 2, Lisein *et al.* 2013; Vermeulen *et al.* 2013), but it is also fundamental in vigilance operations where it is desirable to be undetected by the “intruders” (i.e. anti-poaching).

Current UAS limitations in conservation biology

Although UAS have proven to be useful to perform aerial surveys (Watts *et al.* 2010; Chabot & Bird 2012; Sardà-Palomera *et al.* 2012; Vermeulen *et al.* 2013), or to do vigilance tasks (chapter 2), the systems that are affordable for a common research group (<100,000 €) can operate on a radio of 10-30 km from the ground control station, limiting the current scope of UAS in field biology to missions within that range. Therefore, it is not realistic within the present market scenario to consider substituting a manned aircraft for a UAS in typical wildlife survey campaigns (i.e. periodic aerial censuses in protected areas), but to complement them.

The decrease in UAS prices and payload sensors is one of the favorable circumstances for their integration in ecological research. Particularly, since the last two years there is an emergence of inexpensive (< 3,000 €) UAS in the market, and experienced model aircraft hobbyists may be able to built their own systems for even less than 1,000 €. Very low cost systems may be capable to perform basic missions, but from our experience, reliability of cheap components is low and their failure may cause serious problems producing dangerous situations or diminishing data quality. Usability and quality have a price (Watts *et al.* 2010) and even with the decrease in prices, researchers that want to perform periodic scientific UAS campaigns need to invest a considerable budget to acquire functional and reliable systems.

UAS present some serious operating constraints (Jones *et al.* 2006; Anderson & Gaston 2013): i) UAS usability is determined by favorable weather conditions (less than 15– 20 km/h wind speed for the platform safety and clear atmospheric conditions for good quality images), ii) The legal status of UAS is complicated, a controversial topic in which different agencies (mainly FAA in US and Eurocontrol in Europe) are working. Currently, the situation varies between countries, from a clear prohibition, the possibility of authorized flights with altitude and range restrictions and up to a total absence of regulation, an unclear situation that poses significant limitations to entry for scientific users, iii) there is a need of specialized personnel to operate the systems, some knowledge for maintenance (Jones *et al.* 2006) and some

expertise for data processing, which implies the need of investing time into learning or resources into contracting experts.

As stated by Ellwood *et al.* 2007, who analyzed technology integration in conservation biology: “failure to understand technology limitations can have serious consequences”. Most of ecology studies using UAS are based on image analysis, therefore, experimental design must be carefully matched to avoid “drowning” into thousands of images and so that researchers understand the significance of missing data. Detectability from a UAS depends on the target size, shape, color, shadow, contrast against background and their response to the aircraft (listed by Fleming & Tracey 2008 for manned aerial surveys), but also on the UAS camera characteristics, flight altitude, stability of the aircraft and the environmental conditions. Habitat characteristics such as vegetation cover (Bayliss & Yeomans 1989) also affect animal’s detectability but besides, to select or avoid for cover may vary by species, season and time of day. The inclusion of detectability coefficients (chapter 4) or using automatic pattern recognition techniques into data-processing procedures may improve the process (Abd-elrahman *et al.* 2005) but still, a word of caution should be raised regarding the cost/benefit ratio of the applicability of these systems.

Future prospects of UAS in conservation biology

All the experiments that we conducted in this thesis were performed with small UAS that have limited range and autonomy, constraining the scale of the work and therefore the scope of the research. A more generalized access to larger UAS, which is currently limited to a few international agencies, would allow more experts to address issues of great importance in conservation in a global scale, such as the study of climate change, deforestation and habitat fragmentation, all major causes of biodiversity loss. Although this possibility seems complicated in the short term, it may be feasible through agreements between research and military agencies, at least for sharing some data or to embark scientific equipment in the training missions of large military UAS.

One of the UAS capabilities that has hardly been exploited in small UAS for environmental applications is the inclusion of other sensors different from cameras as payload. Meteorological sensors and sampling devices can provide another insight on vertical habitat characteristics and contribute to understand animal movement patterns, such as birds’ flight dynamics and migration.

UAS may offer new possibilities for conservation biologists if used in combination with other technologies such as biollogging for animal movement studies or static sensors (i.e. surveillance cameras) for vigilance in protected areas. A further step in this line of research would be to make the different systems interact with each other (i.e. static sensors with mobile sensors) and working together forming heterogeneous cooperating objects networks.

Conclusions

This Ph.D. thesis describes the use of small UAS for impact assessment of infrastructures, protection of endangered species, quasi-real time environmental monitoring and to determine animal spatial distribution patterns, demonstrating that these systems can provide useful information in conservation biology.

The main benefits that UAS equipped with embarked sensors bring to conservation biology are:

- 1) Possibility to create tailored systems (interchanging aerial platforms and payloads) adapted for different mission scopes and research requirements.
- 2) Aerial perspective, that offers advantages over ground data collection by saving time and resources or reducing risk for people and providing access to remote areas.
- 3) High spatial resolution images, that allow infrastructures inspection, wildlife monitoring and habitat characterization with more detail and at lower cost than other aerial methods.
- 4) High temporal resolution information that allows environmental monitoring in an easily repeatable way facilitating systematic studies.
- 5) Low impact, beneficial for animals' surveys and protected areas vigilance.

The main limitations for UAS integration in conservation biology are:

- 6) Scope of the missions, constrained by range and autonomy of the systems.
- 7) Budget restrictions. Although UAS prices are decreasing, reliable systems still require a considerable investment.
- 8) Operating constraints: weather conditions, legal restrictions.
- 9) Need of specialized personnel (or investment in specific training) for operating the systems.
- 10) Difficulty to process high volumes of images and to evaluate the significance of missing data (mainly related with detectability problems).

Literature cited

- ABC. (2014). UAS to Monitor Marshlands in New South Wales. *UAS news*, 1–4.
- Abd-elrahman, A., Pearlstine, L. & Percival, F. (2005). Development of Pattern Recognition Algorithm for Automatic Bird Detection from Unmanned Aerial Vehicle Imagery. *Surveying and land information science*, **65**, 37–45.
- Acevedo, P., Quirós-Fernández, F., Casal, J. & Vicente, J. (2014). Spatial distribution of wild boar population abundance: Basic information for spatial epidemiology and wildlife management. *Ecological Indicators*, **36**, 594–600.
- AeryonLabs. (2014). Monitoring sensitive salmon populations on Snake River is safer with Aeryon Scout. *Applications, Case studies*. Retrieved November 27, 2014, from <http://www.aeryon.com/applications/case-studies/588-monitoring-sensitive-salmon-populations-on-snake-river-is-safer-with-aeryon-scout.html>
- Akaike, H. (1974). A new look at the statistical model identification. *IEEE Trans Automat Contr AC* pp. 19:716–723.
- Alcaide, M., Negro, J.J., Serrano, D., Antolín, J.L., Casado, S. & Pomarol, M. (2010). Captive breeding and reintroduction of the lesser kestrel *Falco naumanni*: a genetic analysis using microsatellites. *Conservation Genetics*, **11**, 331–338.
- Anderson, K. & Gaston, K.J. (2013). Lightweight unmanned aerial vehicles will revolutionize spatial ecology. *Frontiers in Ecology and the Environment*, **11**, 138–146.
- Arjomandi, M. (2007). *Classification of Unmanned Aerial Vehicles*. *Mechanical Engineering*. 3016. Adelaide, Australia.
- Averett, N. (2014). Drones Take Off as Wildlife Conservation Tool. *Audubon magazine*, 1–8.
- Bailey, D.W., Gross, J.E., Laca, E.A., Rittenhouse, L.R., Coughenour, M.B., Swift, D.M. & Sims, P.L. (1996). Mechanisms that result in large herbivore grazing distribution patterns. *Journal of Rangeland Management*, **49**, 386–400.

- Bayliss, P. & Yeomans, K. (1989). Correcting bias in aerial survey population estimates of feral livestock in northern Australia using the double-count technique. *Journal of Applied Ecology*, **26**, 925–933.
- Berni, J.A.J., Zarco-Tejada, P., Suárez, L. & Fereres, E. (2009). Thermal and narrowband multispectral remote sensing for vegetation monitoring from an unmanned aerial vehicle. *IEEE Transactions on Geoscience and Remote Sensing*, **47**, 722–738.
- BirdLife International. (2011). Species factsheet: *Falco naumanni*.
- Blackburn, T. & Gaston, K. (1994). The distribution of body sizes of the world's bird species. *Oikos*, 127–130.
- Bluff, L. A. & Rutz, C. (2008). A quick guide to video-tracking birds. *Biology Letters*, **4**, 319–22.
- Blyenburgh, P. Van. (1999). UAVs - Current situation and considerations for the way forward. *Development and Operation of UAVs for Military and Civil Applications* (ed R. EN-9), Rhode, Belgium.
- Bologna, F., Mahatho, N. & Hoch, D. (2002). Infra-red and ultra-violet imaging techniques applied to the inspection of outdoor transmission voltage insulators. *IEEE Africon. Electrotechnical services for Africa* pp. 593–598. IEEE, 345 E 47 Th St. NY 10017 USA, Pretoria, South Africa.
- Braza, F. & Alvarez, F. (1987). Habitat use by red deer and fallow deer in Doñana National Park. *Miscellanea Zoológica*, **11**, 363–367.
- Bugalho, M.N. & Milne, J. A. (2003). The composition of the diet of red deer (*Cervus elaphus*) in a Mediterranean environment: a case of summer nutritional constraint? *Forest Ecology and Management*, **181**, 23–29.
- Campoy, P., García, P.J., Barrientos, A., Cerro, J.D., Aguirre, I., Roa, A., García, R. & Muñoz, J.M. (2001). An stereoscopic vision system guiding an autonomous helicopter for overhead power cable inspection. *International workshop Rob. Vis.* pp 115–124. Auckland, New Zealand.
- Cano, M., Granados, J., Castillo, A., Serrano, E., Pérez, J., Soriguer, R., Fandos, P. & Travesí, R. (2007). Nuevas tecnologías aplicadas al seguimiento de ungulados silvestres en Sierra Nevada: Collares GPS-GSM. *Biodiversidad y conservación de fauna y flora en ambientes mediterráneos*. (ed SGHG), pp. 691–705. Granada.

- Casasús, I., Riedel, J.L., Blanco, M. & Bernués, A. (2012). *Extensive livestock production systems and the environment. In Animal farming and environmental interactions in the Mediterranean region.*
- Chabot, D. & Bird, D.M. (2012). Evaluation of an off-the-shelf Unmanned Aircraft System for Surveying Flocks of Geese. *Waterbirds*, **35**, 170–174.
- Chabot, D. & Bird, D.M. (2013). Small unmanned aircraft: precise and convenient new tools for surveying wetlands. *Journal of Unmanned Vehicle Systems*, **24**, 15–24.
- Chabot, D., Carignan, V. & Bird, D.M. (2014). Measuring Habitat Quality for Least Bitterns in a Created Wetland with Use of a Small Unmanned Aircraft. *Wetlands*, **34**, 527–533.
- Chapman, A. (2014). It ' s okay to call them drones. *Journal of Unmanned Vehicle Systems*, **2**, 1–3.
- CLAVE S.L. (1992). *Análisis de impactos de líneas eléctricas sobre la avifauna de espacios naturales protegidos* (R.E. de E. Compañía Sevillana de Electricidad, Iberdrola, Ed.). Seville, Spain.
- Collinge, S. (2010). Spatial Ecology and Conservation. *Nature Education Knowledge*, **3**, 69.
- Consejería de Medio Ambiente y Ordenación del Territorio. (2013). *Cartografía y evaluación de la vegetación y flora de los ecosistemas forestales de Andalucía a escala de detalle (1:10.000)*. Spain.
- Cooke, S., Hinch, S., Wikelski, M., Andrews, R. & Kuchel, L. (2004). Biotelemetry: a mechanistic approach to ecology. *Trends Ecol Evol*, **19**, 334– 343.
- Coulombe, M.L., Massé, A. & Côté, S.D. (2006). Telemetry Quantification and Accuracy of Activity Data Measured with VHF and GPS Telemetry. *Wildlife Society Bulletin*, **34**, 81–92.
- Cox, T.H., Nagy, C.J., Skoog, M.A. & Somers, I.A. (2004). *Civil UAV capability assessment*. Houston, TX, US.
- Cramp, S. & Simmons, K. (1980). Hawk to Bustards. *Handbook of the Birds of Europe, the Middle East and North Africa. Vol 2*. Oxford University Press, Oxford.

- Crivelli, A.J., Jerrentrup, H. & Mitchev, T. (1988). Electric power lines: a cause of mortality in *Pelecanus crispus* Bruch, a world endangered bird species. *Waterbirds*, **11**, 301–305.
- Crockford, N.J. (1992). *A review of the possible impacts of wind farms on birds and other wildlife*. Peterborough (United Kingdom).
- Dewar, H. (2013). Terrapin 1 drone soars, protecting rhinos from poachers. *News*. Retrieved November 24, 2014, from <https://cmns.umd.edu/news-events/features/1101>
- Van Diermen, J., van Manen, W. & Edwin, B. (2009). Terreingebruik en activiteitspatroon van Wespandieven *Pernis apivorus* op de Veluwe. *Takkeling*, 109–133.
- Dirección general de armamento y material. Ministerio de Defensa de España. (2008). *UAS: sobre su integración en el espacio aéreo no segregado*. Sistema de Observación y prospectiva tecnológica. Observatorio de UAVs, Robótica y Sistemas Aéreos, Spain.
- Donázar, J., Negro, J. & Hiraldo, F. (1993). Foraging habitat selection, land-use changes and population decline in the lesser kestrel *Falco naumanni*. *Journal of Applied Ecology*, **30**, 515–522.
- Dublin, H. (2011). African Elephant Specialist Group Report. *Pachyderm*, **49**, 1–5.
- Duerr, A.E., Miller, T. A, Lanzone, M., Brandes, D., Cooper, J., O'Malley, K., Maisonneuve, C., Tremblay, J. & Katzner, T. (2012). Testing an emerging paradigm in migration ecology shows surprising differences in efficiency between flight modes. *PLoS ONE*, **7**, e35548.
- Dunford, R., Michel, K., Gagnage, M., Piégay, H. & Trémelo, M-L. (2009). Potential and constraints of Unmanned Aerial Vehicle technology for the characterization of Mediterranean riparian forest. *International Journal of Remote Sensing*, **30**, 4915–4935.
- Elliot, J.M. (1977). *Statistical analysis of samples of benthic invertebrates*. (F.B. Association, Ed.). Ambleside.
- Ellwood, S.A., Wilson, R.P. & Addison, A.C. (2007). Technology in conservation: a boon but with small print. *Key topics in Conservation Biology* (eds D.W. Macdonalds & K. Service), p. 329. Blackwell Publishing, Padstow, UK.

- Emslie, R. (2012). www.iucnredlist.org. *Ceratotherium simum*, *Diceros bicornis*. IUCN Red List of Threatened Species. Version 2012.2. Retrieved January 16, 2013, from www.iucnredlist.org
- Emslie, R., African Rhino Specialist Group, I. & Asian Rhino Specialist Group, I. (2013). African Rhinoceroses – Latest trends in rhino numbers and poaching. *Convention on international trade in endangered species of wild fauna and flora. Sixteenth meeting of the conference of the Parties* (ed IUCN), pp. 1–6. Bangkok, Thailand.
- Emslie, R. & Brooks, M. (1999). *Status Survey and Conservation Action Plan African Rhino* (IUCN/SSC African Rhino Specialist Group. IUCN, Ed.). Gland, Switzerland and Cambridge, UK.
- Espacio Natural Doñana. (2000). *Plan de Aprovechamiento ganadero del Parque Nacional de Doñana*. Spain.
- Etherington, T.R., Ward, A.I., Smith, G.C., Pietravallo, S. & Wilson, G.J. (2009). Using the Mahalanobis distance statistic with unplanned presence-only survey data for biogeographical models of species distribution and abundance: a case study of badger setts. *J. Biogeogr.*, 845–853.
- Eustace, M. (2012). Rhino poaching: what's the solution? *Business Day*. 20 January. Retrieved March 8, 2013, from <http://www.bdlive.co.za/articles/2012/01/20/rhino-poaching-what-is-the-solution>
- FAA USA. (2014). FAA. *Unmanned Aircraft Systems (UAS) Frequently Asked Questions*. Retrieved November 23, 2014, from <https://www.faa.gov/uas/faq/>
- Farrell, S.P. (2013). A Drone's-Eye View of Nature. *New York Times*.
- Ferreira, S.M., Botha, J.M. & Emmett, M.C. (2012). Anthropogenic influences on conservation values of white rhinoceros. *PLoS ONE*, 7, e45989.
- Ferrer, M. (2012). *Birds and power lines*, Firstn. (F. MIGRES, Ed.). Seville, Spain.
- Ferrer, M. & Hiraldo, F. (1991). Evaluation of management techniques for the Spanish imperial eagle. *Wildlife Society Bulletin*, 19, 436–442.
- Ferrer, M. & Janss, G. (1999). *Birds and power lines* (Quercus, Ed.). Madrid, Spain.

- Ferrer, M., de la Riva, M. & Castroviejo, J. (1991). Electrocution of raptors on power lines in Southern Spain. *Jour. Field Ornithol.*, **62**, 54–69.
- Ferrer, M. & Negro, J. (1992). Tendidos eléctricos y conservación de aves en España. *Ardeola*, **39**, 23–27.
- Finn, R.L. & Wright, D. (2012). Unmanned aircraft systems: Surveillance, ethics and privacy in civil applications. *Computer Law & Security Review*, **28**, 184–194.
- Fleming, P. & Tracey, J. (2008). Some human, aircraft and animal factors affecting aerial surveys: how to enumerate animals from the air. *Wildlife Research*, 258–267.
- Forman, R.T.T. & Alexander, L.E. (1998). Roads and their major ecological effects. *Annu. Rev. Ecol. Syst.*, **29**, 207–231.
- Fornace, K.M., Drakeley, C.J., William, T., Espino, F. & Cox, J. (2014). Mapping infectious disease landscapes: unmanned aerial vehicles and epidemiology. *Trends in Parasitology*, 1–6.
- Frair, J., Nielsen, S., Merrill, E., Lele, S., Boyce, M. & et al. (2004). Removing GPS collar bias in habitat selection studies. *J Appl Ecol*, **41**, 201–212.
- Franco, A., Catry, I., Sutherland, W. & Palmeirim, J. (2004). Do different habitat preference survey methods produce the same conservation recommendations for lesser kestrels? *Anim Cons*, 291–300.
- Gaillard, J.-M., Hebblewhite, M., Loison, A., Fuller, M., Powell, R., Basille, M. & Van Moorter, B. (2010). Habitat–performance relationships: finding the right metric at a given spatial scale. *Phil. Trans. R. Soc. B*, 2255–2265.
- Gemert, J., Verschoor, C.R., Mettes, P., Epema, K., Koh, L.P. & Wich, S. (2014). Nature Conservation Drones for Automatic Localization and Counting of Animals. *Computer Vision in vehicle technology with Special Session on Micro Aerial Vehicles* Zurich, Switzerland.
- Getzin, S., Wiegand, K. & Schöning, I. (2012). Assessing biodiversity in forests using very high-resolution images and unmanned aerial vehicles. *Methods in Ecology and Evolution*, **3**, 397–404.
- Gibson, R. & Guinness, F. (1980). Behavioural factors affecting male reproductive success in red deer (*Cervus elaphus*). *Animal Behaviour*, **28**, 1163–1174.

- Gobierno de España. (2005). Orden PRE/1841/2005 sobre zonas prohibidas y restringidas al vuelo. 20886–20889.
- Gordon, I.J. (1995). Animal based techniques for grazing ecology research. *Small Ruminant Research*, **16**, 203–214.
- Gortázar, C., Torres, M.J., Vicente, J., Acevedo, P., Reglero, M., de la Fuente, J., Negro, J.J. & Aznar-Martín, J. (2008). Bovine tuberculosis in Doñana Biosphere Reserve: the role of wild ungulates as disease reservoirs in the last Iberian lynx strongholds. *PLoS ONE*, **3**, e2776.
- Grémillet, D., Mullers, R., Moseley, C., Pichegru, L., Coetzee, J., Sabarros, P., van der Lingen, C., Ryan, P., Kato, A. & Ropert-Coudert, Y. (2010). Seabirds, fisheries, and cameras. *Frontiers in Ecology and the Environment*, 401–402.
- Grenzdörffer, G. (2013). *UAS-based automatic bird count of a common gull colony*. Rostock, Germany.
- Han, S., Hao, R. & Lee, J. (2009). Inspection of insulators on high-voltage power transmission lines. *The 4th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI 2007)* pp. 51–56.
- Hodgson, A., Kelly, N. & Peel, D. (2013). Unmanned Aerial Vehicles (UAVs) for Surveying Marine Fauna: A Dugong Case Study (B. Fenton, Ed.). *PLoS ONE*, **8**, e79556.
- Hosmer, D.W. & Lemeshow, S. (2000). Applied Logistic Regression. *Model-Building Strategies and Methods for Logistic Regression*. (ed Wiley), pp. 91–142. New York, USA.
- ICAO. (2011). *Unmanned Aircraft Systems (UAS) ICAO Cir 328*. John Wiley & Sons, Ltd, Chichester, UK.
- Ingham, L., Jones, T. & Maneschijn, A. (2006). Considerations for UAV design and operation in South African airspace. *The Aeronautical Journal*, **October**, 695–701.
- Israel, M. (2011). A UAV-Based Roe Deer Fawn Detection System. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, **XXXVIII**, 51–55.

- JAPCC (Joint Air Power Competence Centre). (2010). *Strategic concept of employment for Unmanned Aircraft Systems in NATO*. Kalkar, Germany.
- Jefatura del Estado. (2014). Ley 18/ 2014. BOE, Sec. 6, art. 50. 83976–83981.
- Jerde, C. & Visscher, D. (2005). GPS measurement error influences on movement model parameterization. *Ecol Appl*, **15**, 806–810.
- Jones, G.P. (2003). *The feasibility of using Small Unmanned Aerial Vehicles for wildlife research*. University of Florida.
- Jones, G., Pearlstine, L. & Percival, H. (2006). An assessment of small unmanned aerial vehicles for wildlife research. *Wildlife Society Bulletin*, **34**, 750–758.
- Jones, D.I., Whitworth, C.C., Earp, G.K. & Duller, A.W.G. (2005). A laboratory test-bed for an automated power line inspection system. *Control Engineering Practice*, **13**, 835–851.
- Katrasnik, J., Pernus, F. & Likar, B. (2008). New Robot for Power Line Inspection. *IEEE Conference on Robotics, Automation and Mechatronics* (ed IEEE), pp. 1195–1200. Ieee, Chengdu. China.
- Katrašnik, J., Pernuš, F. & Likar, B. (2008). A Climbing-Flying Robot for Power Line Inspection. *IEEE Conference on robotics, Automation and Mechatronics* pp. 95–110.
- Kenward, R. (2001). *A manual for wildlife radiotagging*. (A. Press, Ed.). London, UK.
- Kingsford, R.T. (2000). Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology*, **25**, 109–127.
- Knight, M. (2011). African Rhino Specialist group report. *Pachyderm*, 6–15.
- Koh, L. & Wich, S. (2012). Dawn of drone ecology: low-cost autonomous aerial vehicles for conservation. *Tropical Conservation Science*, **5**, 121–132.
- Körner, F., Speck, R., Göktoğan, A.H. & Sukkarieh, S. (2010). Autonomous airborne wildlife tracking using radio signal strength. *The 2010 IEEE/RISJ International Conference on Intelligent Robots and Systems* pp. 107–112. Taipei.
- Koski, W.R., Allen, T., Ireland, D., Buck, G., Smith, P.R., Macrander, a. M., Halick, M. a., Rushing, C., Sliwa, D.J. & McDonald, T.L. (2009). Evaluation of an

- Unmanned Airborne System for Monitoring Marine Mammals. *Aquatic Mammals*, **35**, 347–357.
- Laliberte, A.S., Goforth, M. A., Steele, C.M. & Rango, A. (2011). Multispectral Remote Sensing from Unmanned Aircraft: Image Processing Workflows and Applications for Rangeland Environments. *Remote Sensing*, **3**, 2529–2551.
- Lazo, A. (1995). Ranging behaviour of feral cattle (*Bos taurus*) in Donana National Park, SW Spain. *Journal of Zoology*, **236**, 359–369.
- Lee, K. (2004). *Development Of Unmanned Aerial Vehicle (UAV) for Wildlife Surveillance*. University of Florida.
- Leonardo, M., Jensen, A.M., Coopmans, C., McKee, M. & Chen, Y. (2013). A Miniature Wildlife Tracking UAV Payload System Using Acoustic Biotelemetry. *Volume 4: 18th Design for Manufacturing and the Life Cycle Conference; 2013 ASME/IEEE International Conference on Mechatronic and Embedded Systems and Applications* p. V004T08A056. ASME.
- Lever, C. (2004). The impact of traditional Chinese medicine on threatened species. *Oryx*, **38**, 13–14.
- Li, Z. & Ruan, Y. (2010). Autonomous Inspection Robot for Power Transmission Lines Maintenance While Operating on the Overhead Ground Wires. *International Journal of Advanced Robotic Systems*, **7**, 107–112.
- Linchant, J., Vermeulen, C., Lisein, J., Lejeune, P. & Bouché, P. (2013). Utiliser les drones pour compter les éléphants: une nouvelle approche des inventaires de faune. *31st Congress of the International Union of Game Biologists* Bruxelles, Belgique.
- Lisein, J., Linchant, J., Lejeune, P., Bouché, P. & Vermeulen, C. (2013). Aerial surveys using an Unmanned Aerial System (UAS): comparison of different methods for estimating the surface area of sampling strips. *Tropical Conservation Science*, **6**, 506–520.
- Loon, R. & Polakow, D. (1997). A conceptual model for assessing the economic feasibility of harvesting African rhinoceros horn. *South African journal of science*, **93**, 237–240.
- López-López, P., Ferrer, M., Madero, A., Casado, E. & McGrady, M. (2011). Solving man-induced large-scale conservation problems: the Spanish imperial eagle and power lines. *PLoS ONE*, **6**, e17196.

- Lovelace (Jr.), D.C. & Boon, K. (2014). *The Drone Wars of the 21st Century: Costs and Benefits Volume 133. Terrorism Series* (O.U. Press, Ed.). Oxford, UK.
- Ma, L. & Chen, Y. (2004). *Aerial surveillance system for overhead power line inspection*. Utah, USA.
- Mamba, A. (2009). Regulation of Unmanned Aircraft Systems in South Africa. Unmanned Aircraft Systems Programme Office (UASPO).
- Mander, D. (2013). Rise of the drones. *Africa Geographic*, 52–55.
- Manly, B.F. (2002). Estimating a resource selection function with line transect sampling. *Journal of Applied Mathematics and Decision Sciences*, **6**, 213–228.
- Martin, J., Edwards, H.H., Burgess, M. a, Percival, H.F., Fagan, D.E., Gardner, B.E., Ortega-Ortiz, J.G., Ifju, P.G., Evers, B.S. & Rambo, T.J. (2012). Estimating distribution of hidden objects with drones: from tennis balls to manatees. *PLoS ONE*, **7**, e38882.
- Martin, E. & Martin, C. (2010). Enhanced community support reduces rhino poaching in Nepal. *Pachyderm*, 48–56.
- Mcdonald, L.L., Erickson, W.P., Boyce, M.S. & Alldredge, J.R. (2012). Modeling vertebrate use of terrestrial resources. *The wildlife techniques manual: Volume 1: Research* (ed The Johns Hopkins University Press), pp. 410–429. Baltimore, Maryland, USA.
- Milledge, S. (2007). Illegal killing of African rhinos and horn trade, 2000-2005: the era of resurgent markets and emerging organized crime. *Pachyderm*, 96–107.
- Millspaugh, J., Sartwell, J., Gitzen, R., Moll, R. & Beringer, J. (2008). A pragmatic view of animal-borne video technology – Response. *Trends Ecol Evol*, 294– 295.
- Moll, R.J., Millspaugh, J.J., Beringer, J., Sartwell, J. & He, Z. (2007). A new “view” of ecology and conservation through animal-borne video systems. *Trends in ecology & evolution*, **22**, 660–8.
- Morellet, N., Klein, F. & Andersen, R. (2010). The census and management of populations of ungulates in Europe. *Ungulate Management in Europe: Problems and Practices* (eds R. Putman, M. Apollonio & R. Andersen), Cambridge University Press.

- Morrison, M.L., Marcot, B. & Mannan, W. (2006). *Wildlife-Habitat relationships. Concepts and applications* (Island Press, Ed.). Washington, USA.
- Mulero-Pázmány, M., Negro, J.J. & Ferrer, M. (2014a). A low cost way for assessing bird risk hazards in power lines: Fixed-wing small unmanned aircraft systems. *Journal of Unmanned Vehicle Systems*, **2**, 5–15.
- Mulero-Pázmány, M., Stolper, R., van Essen, L.D., Negro, J.J. & Sassen, T. (2014b). Remotely piloted aircraft systems as a rhinoceros anti-poaching tool in Africa. *PLoS ONE*, **9**, e83873.
- Murray, D.L. & Fuller, M.R. (2000). A critical review of the effects of marking. *Research Techniques in Animal Ecology: Controversies and Consequences* (eds L. Boitani & T.K. Fuller), pp. 15–65. Columbia University Press.
- Nathan, R. (2008). An emerging movement ecology paradigm. *PNAS*, **105**, 19050–1.
- Negro, J.J. (1987). Adaptación de los tendidos eléctricos al entorno. *Monografías de Alytes*, **REC�**, **1**.
- Negro, J. (1997). Lesser kestrel *Falco naumanni*. *BWP Update*.
- Negro, J.J. & Ferrer, M. (1995). Mitigating measures to reduce electrocution of birds on power lines: a comment on Bevanger’s review. *Ibis*, **147**, 423–424.
- Negro, J., Sarasola, J. & Barclay, J. (2007). Augmenting wild populations and food resources. *Raptor conservation and management techniques* (eds D. Bird & K. Bildstein), pp. 401–410. Hancock House Publishers, Surrey, British Columbia.
- NOAA. (2014). NOAA UAS programs. Retrieved November 26, 2014, from <http://uas.noaa.gov>
- NOVA. (2002). Time Line of UAVs. *Spies that fly*. Retrieved November 23, 2014, from <http://www.pbs.org/wgbh/nova/spiesfly/uavs.html>
- Olendorff, R.R., Miller, A.D. & Lehman, R.N. (1981). *Suggested practices for raptor protection on power lines: the state of the art in 1981*. Utah, USA.
- Olivares-Mendez, M.A. & Bisschand, F. (2013). The NOAA Project : Giving a Chance to Threatened Species in Africa with UAVs. *AFRICOMM 2013 Fifth International*

- Conference on e-Infrastructure and e-Services for Developing Countries* pp. 1–11. Blantyre, Malawi.
- Oxford University Press. (2014). Oxford dictionary. Retrieved November 23, 1BC, from <http://www.oxforddictionaries.com>
- Paneque-Gálvez, J., McCall, M., Napoletano, B., Wich, S. & Koh, L. (2014). Small Drones for Community-Based Forest Monitoring: An Assessment of Their Feasibility and Potential in Tropical Areas. *Forests*, **5**, 1481–1507.
- Pearce, J. & Ferrier, S. (2000). Evaluating the predictive performance of habitat models developed using logistic regression. *Ecological modelling*, **133**, 225–245.
- Pereira, E., Bencatel, R., Correia, J., Félix, L., Gonçalves, G., Morgado, J. & Sousa, J. (2009). Unmanned Air Vehicles for coastal and environmental research. *Journal of Coastal Research*.
- Pérez-Granados, C. (2010). Diet of adult Lesser kestrels *Falco Naumanni* during the breeding season in Central Spain. *Ardeola*, **57**, 443–448.
- Peungsungwal, S., Pungsiri, B., Chammongthai, K. & Okuda, M. (2001). Autonomous robot for a power transmission line inspection. *IEEE International Symposium on circuits and systems (ISCAS 2001)*
- Pomarol, M. (1993). Lesser Kestrel recovery project in Catalonia. *Biology and conservation of small falcons: Proceedings of the 1991 Hawk and Owl Trust Conference*. (eds M. Nicholls & R. Clarke), pp. 24–28. The Hawk and Owl Trust, London.
- Potapov, E.R., Utekhina, I.G., McGrady, M.J. & Rimlinger, D. (2013). Usage of UAV for Surveying Steller ' s Sea Eagle Nests. *Raptors Conservation*, **27**, 253–260.
- Pyper, W. (2008). Population survey pilots an unmanned aircraft. *ECOS*, 17.
- Qamar, F.M., Ali, H., Ashraf, S., Daud, A., Gillani, H., Mirza, H. & Rehman, H.U. (2011). Distribution and habitat selection mapping of key fauna species in selected areas of Western Himalaya, Pakistan. *The Journal of Animal and Plant Sciences*, **21**, 396–399.
- QGIS Development Team. (2012). QGIS Geographic Information System Open Source Geospatial Foundation Project.

- R Foundation for Statistical Computing, Vienna, A. (2013). R: A Language and Environment for Statistical Computing.
- Red Eléctrica. (2005). *Red Eléctrica y la avifauna: 15 años de investigación aplicada* (R.E. de España, Ed.). Seville, Spain.
- Redfern, J. V., Viljoen, P.C.P., Kruger, J.M.M. & Getz, W.. M. (2002). Biases in estimating population size from an aerial census: a case study in the Kruger National Park, South Africa. *South African journal of science*, **98**, 455–461.
- Ribeiro, E. (2007). *Seasonal variation in foraging habitat preference in Lesser Kestrel Falco naumanni*. Universidade de Aveiro, Aveiro, Portugal.
- Rodríguez, A., Negro, J.J., Bustamante, J., Fox, J.W. & Afanasyev, V. (2009). Geolocators map the wintering grounds of threatened Lesser Kestrels in Africa. *Diversity and Distributions*, **15**, 1010–1016.
- Rodríguez, A., Negro, J.J., Mulero, M., Rodríguez, C., Hernández-Pliego, J. & Bustamante, J. (2012a). The eye in the sky: combined use of unmanned aerial systems and GPS data loggers for ecological research and conservation of small birds. *PLoS ONE*, **7**, e50336.
- Rodríguez, A. & Rodríguez, B. (2009). Attraction of petrels to artificial lights in the Canary Islands: effects of the moon phase and age class. *Ibis*, **151**, 299–310.
- Rodríguez, A., Rodríguez, B., Curbelo, Á.J., Pérez, A., Marrero, S. & Negro, J.J. (2012b). Factors affecting mortality of shearwaters stranded by light pollution (T. Katzner, Ed.). *Animal Conservation*, **15**, 519–526.
- Rodríguez, C., Tapia, L., Kieny, F. & Bustamante, J. (2010). Temporal changes in lesser kestrel (*Falco naumanni*) diet during the breeding season in southern Spain. *J Raptor Res*, 120–128.
- Rodríguez, C. & Wiegand, K. (2009). Evaluating the trade-off between machinery efficiency and loss of biodiversity-friendly habitats in arable landscapes: The role of field size. *Agriculture, Ecosystems & Environment*, **129**, 361–366.
- Room, M.H.M. & Ahmad, a. (2014). Mapping of a river using close range photogrammetry technique and unmanned aerial vehicle system. *IOP Conference Series: Earth and Environmental Science*, **18**, 012061.

- Robert-Coudert, Y. & Wilson, R. (2005). Trends and perspectives in animal- attached remote sensing. *Front Ecol Environ*, **3**, 437–444.
- Rutz, C. & Bluff, L. (2008). Animal borne imaging takes wing, or the dawn of “wildlife video-tracking.” *Trends Ecol Evol*, 292–294.
- Rutz, C., Bluff, L., Weir, A. & Kacelnik, A. (2007). Video cameras on wild birds. *Science*, 765.
- Rutz, C. & Hays, G.C. (2009). New frontiers in biologging science. *Biology letters*, **5**, 289–92.
- SACAA. (2008). Interim policy for civil Unmanned Aircraft Systems in South Africa. Second draft.
- Sakamoto, K.Q., Takahashi, A., Iwata, T. & Trathan, P.N. (2009). From the eye of the albatrosses: a bird-borne camera shows an association between albatrosses and a killer whale in the Southern Ocean. *PLoS ONE*, **4**, e7322.
- SAMAA. (2001). Manual of procedure for model aircraft and remote-piloted air vehicle operation.
- Sardà-Palomera, F., Bota, G., Viñolo, C., Pallarés, O., Sazatornil, V., Brotons, L., Gomáriz, S. & Sardà, F. (2012). Fine-scale bird monitoring from light unmanned aircraft systems. *Ibis*, **154**, 177–183.
- SCB. (2014). Society for Conservation Biology. Retrieved November 25, 2014, from <http://www.conbio.org>
- Schiffman, R. (2014). Drones Flying High as New Tool For Field Biologists. *Science*, **344**, 2014.
- Schwarzbach, M., Laiacker, M., Mulero-Pazmany, M. & Kondak, K. (2014). Remote water sampling using flying robots. *2014 International Conference on Unmanned Aircraft Systems (ICUAS)*, 72–76.
- Shepard, E., Lambertucci, S., Vallmitjana, D. & Wilson, R. (2011). Energy Beyond Food: Foraging Theory Informs Time Spent in Thermals by a Large Soaring Bird. *Plos One*, e27375.

- Silvy, N.J., Lopez, R.R. & Peterson, M.J. (2012). Wildlife Marking Techniques. *The Wildlife Techniques Manual*. (ed N.J.Silvy), pp. 230–257. Baltimore, MD, USA.
- Soriano, P., Caballero, F. & Ollero, A. (2009). RF-based Particle Filter localization for Wildlife Tracking by using an UAV. *40 th International Symposium of Robotics*. pp. 239–244. Barcelona, España.
- Soulé, M.E. (2007). What is Conservation Biology? *BioScience*, **35**, 727–734.
- Stolper, R., Hart, J. & Mahatho, N. (2009). The design and evaluation of a multi-spectral imaging camera for the inspection of transmission lines and substation equipment. *Insulator News Magazine Report*, 1–14.
- Teal Group. (2014). *Teal Group Predicts Worldwide UAV Market Will Total \$91 Billion in Its 2014 UAV Market Profile and Forecast*. Paris, France.
- Tella, J., Forero, M., Hiraldo, F. & Donázar, J. (1998). Conflicts between Lesser Kestrel conservation and European Agricultural Policies as identified by habitat analyses. *Cons Biol*, 593–604.
- Tellería, J.L. (1986). *Manual para el censo de los vertebrados terrestres* (Raíces, Ed.). Madrid.
- Tesla, N. (1898). Method of and apparatus for controlling mechanism of moving vessels or vehicles.
- Tracey, J.P., Fleming, P.J.S. & Melville, G.J. (2008). Accuracy of some aerial survey estimators: contrasts with known numbers. *Wildlife Research*, **35**, 377.
- U.S. Army. (2010). *Eyes of the Army – Unmanned Aircraft Systems. Roadmap 2010–2035*. Fort Rucker, Alabama, US.
- UK Ministry of Defence. (2010). *Unmanned Aircraft Systems: Terminology, Definitions and Classification. Joint Doctrine Note 3/10*. Wiltshire, UK.
- UNESCO. (2014). World heritage list. Retrieved February 5, 2014, from <http://whc.unesco.org/en/list/685>
- Ursua, E., Serrano, D. & Tella, J. (2005). Does land irrigation actually reduce foraging habitat for breeding lesser kestrels? The role of crop types. *Biological Conservation*, **122**, 643–648.

- US Department of Defense. (2014). US DoD. *UAV Unmanned Aerial Vehicles*. Retrieved November 23, 1BC, from <http://www.defense.gov/specials/uav2002/>
- Valavanis, K.P. (2008). *Advances in Unmanned Aerial Vehicles: State of the Art and the Road to Autonomy. Volume 33 of Intelligent Systems, Control and Automation: Science and Engineering* (S.S.& B. Media, Ed.). Dordrecht, The Netherlands.
- Vermeulen, C., Lejeune, P., Lisein, J., Sawadogo, P. & Bouché, P. (2013). Unmanned Aerial Survey of Elephants. *PLoS ONE*, **8**, e54700.
- Viitala, J., Korplmäki, E., Palokangas, P. & Koivula, M. (1995). Attraction of kestrels to vole scent marks visible in ultraviolet light. *Nature*, **373**, 425–427.
- Watts, A.C., Bowman, W.S., Abd-Elrahman, A.H., Mohamed, A., Wilkinson, B.E., Perry, J., Kaddoura, Y.O. & Lee, K. (2008). Unmanned Aircraft Systems (UASs) for ecological research and natural-resource monitoring (Florida). *Ecological Restoration*, **26**, 10–15.
- Watts, A.C., Perry, J.H., Smith, S.E., Burgess, M. A., Wilkinson, B.E., Szantoi, Z., Ifju, P.G. & Percival, H.F. (2010). Small Unmanned Aircraft Systems for Low-Altitude Aerial Surveys. *Journal of Wildlife Management*, **74**, 1614–1619.
- WcUAVC. (2013). Wildlife Conservation UAV Challenge. Retrieved December 20, 2013, from <http://www.wcuavc.com/>
- Whitworth, C., Duller, A., Jones, D. & Earp, G. (2001). Aerial video inspection of overhead power lines. *Power Engineering Journal*, **15**, 25–32.
- Wild, S. (2013). Drones now part of anti-poaching arsenal. *Bussines day*. Retrieved March 10, 2013, from <http://www.bdlive.co.za/national/science/2013/02/08/drones-now-part-of-anti-poaching-arsenal>
- Wilkinson, B.E. (2007). *The design of the georeferencing techniques for unmanned autonomous aerial vehicle video for use with wildlife inventory surveys: a case study of the National Bison Range, Montana*. University of Florida.
- Williamson, S.P. (2011). *Utilization of Unmanned Aircraft Systems for Environmental Monitoring*. Silver Spring, Maryland.

WWF. (2013). Google Helps WWF Stop Wildlife Crime. Retrieved May 3, 2013, from <http://worldwildlife.org/stories/google-helps-wwf-stop-wildlife-crime>

Zavalaga, C.B., Dell’Omo, G., Becciu, P. & Yoda, K. (2011). Patterns of GPS tracks suggest nocturnal foraging by incubating Peruvian pelicans (*Pelecanus thagus*). *PLoS ONE*, **6**, e19966.

Zenko, M. (2013). *Reforming U . S . Drone Strike Policies. Council Special Report No. 65*. Washington, USA.

Acknowledgements

This thesis would not have happened without the work of many people over nearly ten years that have contributed in one way or another to this line of research. First, I must mention my father Manuel Mulero, pioneer in the development of UAS at INTA, since it was he who suggested the use of these systems in field biology tasks. Those days with the family in the airfields in Guadalajara where we flew his model planes and the passion for aviation that he has always transmitted to me are quite responsible that I ended up in this subject. In addition, he taught me the basics about the systems and facilitated the first contacts with the few Spanish manufacturers that back in 2005 produced systems that could be adapted to the objectives (mainly SCR and UAV Navigation).

After many years of maturation, countless meetings with stakeholders, writing drafts, preparation of proposals, and seeking funds, finally the idea began to materialize in the SADCON project, which later led to the AEROMAB and PLANET projects in which I have worked thanks to the essential support of Dr. Miguel Ferrer, Dr. Juan José Negro (Doñana Biological Station directors in different periods) and Dr. Aníbal Ollero (Professor of Robotics U. Sevilla) who demonstrated their interest getting engaged in the development of this new line of research in Spain. I am also grateful to the institutions that funded the projects where I could work in Doñana Biological Station: AEROMAB (Andalusia Government, Project for Excellence, 2007, P07-RNM-03246) and PLANET (European Commission 7th FP Grant Agreement No. 257649).

The most fruitful period that led to the manuscripts contained in this thesis has taken place in the last five years that I have worked with Dr. Juan José Negro, whom I would like to thank for trusting and supporting me as supervisor in this thesis. I thank my tutor Carlos Granado and the director of the doctoral program, Juan Arroyo, for their kind cooperation, essential for the realization of the thesis at the University of Seville.

I also thank the contributions of my thesis committee: Pedro Marrón and Marc Schwarzbach have contributed with valuable suggestions to address the topic from a multidisciplinary perspective and Manuela González Suárez has been my scientific referent in regard to biology, contributing with ideas, reviewing manuscripts and helping me patiently in the statistics.

Chapter 2 is the result of a collaborative campaign with CSIR and CWM (Univ. Pretoria) conducted in South Africa in 2012. I am very grateful to Roel Stolper for propitiating this experience and to all members of the rhinoceros anti-poaching team for facilitating our work in Kwa-Zulu Natal. LD van Essen helped a lot at work, answered my endless questions about ecology and tracks of African animals, welcomed us into his lovely home and cooked the best braais of the southern hemisphere... All, even though we crashed the plane on his friend's farm fence on the very first flight of the campaign.

I thank Airam Rodríguez, Jesús Hernández Pliego, Carlos Rodríguez and Javier Bustamante, co-authors of Chapter 3, for allowing me to include it in this thesis, and the LAST-DBS team for their help in data processing.

The support of IREC team has been fundamental for the development of chapter 4. I really appreciate the patient dedication of José Barasona, the kindness from Joaquín Vicente and the statistical advice of Pelayo Acevedo, in addition to the fantastic welcome I received from all of them during my brief but intense stay in Ciudad Real.

My thanks also go to the technicians who participated in the fieldwork: Luna Puentes made a commendable effort to learn to pilot UAS; Jorge Gutiérrez adapted our systems to the requirements of the field; Esteban Guerrero processed most of the data and provided a lot of emotions with his unique take-offs; and finally to Miguel Angel Aguilar, the best pilot, capable of finding solutions to any technical problem and with a "gaditano" sense of humor that made work much more fun. Eladio and Javi Martínez (Electronica RC) and Piero (Modelexpert) were the main suppliers of most of the components of the UAS, but also our teachers, consultants and aircraft forensic doctors. Saeta and Bollullos de la Mitación Radio-Control Clubs have also contributed to the successful development of this work, as we performed the tests in their airfields before flying in the final scenarios. The colleagues were always very kind with us, they allowed me to take my dog Faro to the airfield and some mornings they generously shared tortilla, beer and chorizo with us. The volunteers who participated in data collection of the experiments deserve a special recognition for their efforts and enthusiasm. I remember Kike Sanchez, Belinda Santos, Paloma and Mari Cuesta with particular fondness.

Part of the fieldwork for this thesis was carried out in the Doñana National Park, thanks to the park authorities permission and the collaboration of Doñana Biological Reserve staff. I would like to dedicate a special acknowledgement to Fernando Ibáñez and the rangers for their effective logistical support. The people

from Palacio and Huerta Tejada made our stays in the field a pleasure, especially Fabiola with her nice smile and Cecilia with her jokes that made me laugh so much. I also appreciate the work of the administration people in the Doñana Biological Station who helped me with the financial justification of projects and other bureaucratic tasks, including everything necessary for me to get paid at the end of the month.

Although they have not been directly involved in this work, José Luis Tellería with his fantastic classes at the U. Complutense and the words and texts by Miguel Delibes are responsible for my conservationist vocation and have always been a source of inspiration.

Miguel Ferrer deserves special thanks since he influenced in my early steps on science. He facilitated my first stay as a volunteer in Doñana when I was a teenager hesitant to enroll in biology or aeronautical engineering. That summer following booted eagles in the marshlands assisting Javier Balbontín (who was working in his thesis with Miguel) convinced me to study biology, although ultimately I have combined flying animals and machines. Miguel's practical vision about the role of the biologist in society and his open mind to multidisciplinary collaboration contributed substantially to the takeoff of the UAS adventure.

All the research of UAS for environmental applications would not have been possible without the participation of Aníbal Ollero, a great engineer who despite a crazy agenda found time and desires to explore new ideas and to get funding for carry them out.

As this thesis collects some of the work done in recent years, I would like to express a big THANK YOU to the people with whom I have shared this period in my life:

To my colleagues at the office: I appreciate your attention for answering my questions and the good times we have enjoyed together. In particular, I feel a special affection and admiration for David Canal, a gentleman in one of those situations where only those who are gentlemen behave as such. Lorenzo had to sit next to me at a difficult time, I appreciate your wise scientific advice and the pleasure to talk about things other than science (and if I find the meteorite I will give you a piece).

Life in the EBD and the Reserve had not been the same without the "puppies" of different litters with whom I shared meals talking about disgusting issues in the non-canteen, sunshine on the steps, beach days in the Pichilín, tapeos in Seville, anti-mosquito lotion in the marshlands and nights of party and stars in the Palacio.

Acknowledgements

Mara Viota, Carol, Zulima, Nuno, Irene, Ugo, Letizia, Alessandro, Simone, Fernando, Luis, Alicia, Lidia, Andrea, Chris, Cande, Gemma, Miguel, Laura, Alvarito, Rubén, Pablo and many more... Thanks for all the good times.

Special thanks to the MA teammates: Marcello D'Amico (well written?, lol) for the four house movings in which you have carried my piano, for believing in me more than me and for showing me the positive side of everything with your spectacular calm, and Manuela González for removing my ticks on the African savannah, for supporting me and helping me to get up when I came down, for your intelligence, kindness, and everything I learn every day from you "queridah amigah" .

Miguel Angel Bravo and Ana Popa, so many years and kilometers traveled together! To you, always there, what can I say here that you do not know already? I love you very much and I love to argue with you!.

This Andalusian stage in my life has been very special thanks to lots of friends that I would like to thank: my faithful servant Pablo, Jaume for his infinite capacity to listen, to Pedro Luis Mozo for “flying” with me in a car and giving me good books, Isidro for helping me to steal the best dog in Portugal, the flatmates: Emily, Nick, Ines, Ana, Max and Carlo for the good times in the coolest apartment of Triana and to Paco Vega, Matías de las Heras and Andres de la Cruz for putting up my bad times and always making me laugh. Thanks also to my Maestro Antonio Cotán, we both know that taming a horse is much more complicated than any thesis and thanks to Serengeti for being so difficult and keeping us entertained on the task.

I also want to thank those that were always there, welcoming me in the short notice visits (sorry) as if I had never left Madrid: Pati, Irene, Nat, Lorenzana, Elena and Ana; and Almería: Ana, Carlos, Alfonsito and Andrés. And of course, to the colleagues with whom I discovered amazing places in this world generating beautiful memories: Christian, Mónica, David, Cristina and Adolf.

Finally, precisely because it is the most important, I thank my family, that although geographically dispersed has supported me in all: my mother, infinite goodness, my father, my brother (Love you brother!), the Barcelona crazy fun family, my grandmother who should be scientific, my grandfather who would have enjoyed this thesis, Carmen and Jacinto that are also family. And Faro, my best friend, who was always by my side.

Thank you all!

Agradecimientos

Esta tesis no hubiera podido realizarse si no fuera por el trabajo de numerosas personas que a lo largo de casi diez años han participado de una manera o de otra en esta línea de investigación. En primer lugar debo mencionar a mi padre Manuel Mulero, pionero en el desarrollo de aviones no tripulados en el INTA, ya que fue él quien me sugirió explorar el uso de estos sistemas en tareas de biología de campo. Las jornadas con toda la familia en los campos de aeromodelismo en Guadalajara, donde volábamos sus aviones de madera de balsa hace ya muchos años y la pasión que siempre me ha transmitido por la aviación han tenido gran parte de la culpa de yo acabara en este tema. Además, él me dio las nociones básicas sobre los equipos y me facilitó los primeros contactos de empresas fabricantes, las pocas españolas que allá por 2005 producían sistemas que pudieran adaptarse a los objetivos (principalmente SCR y UAV Navigation).

Tras muchos años de maduración, innumerables reuniones con los agentes interesados, redacción de borradores, elaboración de propuestas de trabajo y búsqueda de financiación, finalmente la idea empezó a materializarse en el proyecto SADCON, que a su vez dio lugar a los proyectos AEROMAB y PLANET en los que he podido trabajar gracias al apoyo del Dr. Miguel Ferrer, Dr. Juan José Negro (directores de la Estación Biológica de Doñana en distintos periodos) y al Dr. Aníbal Ollero (Catedrático de Robótica de la U. Sevilla), que demostraron su interés apostando por el desarrollo de esta línea de investigación novedosa en España. Agradezco también a las entidades correspondientes la financiación de los proyectos en los que he podido trabajar a través de la Estación Biológica de Doñana: AEROMAB (Junta de Andalucía, Proyectos de Excelencia, 2007, P07-RNM-03246) y PLANET (European Commission 7th FP Grant Agreement No. 257649).

La etapa más fructífera que ha conducido a los manuscritos que contiene este trabajo ha tenido lugar en los últimos cinco años en los que he trabajado con el Dr. Juan José Negro, a quien me gustaría dar las gracias por confiar en mí y respaldarme como supervisor de tesis. A mi tutor Carlos Granado y al director del programa de doctorado, Juan Arroyo, les agradezco su amable colaboración, imprescindible para la realización de la tesis en la Universidad de Sevilla.

Agradezco también las aportaciones de mi comité de tesis: Pedro Marrón y Marc Schwarzbach han contribuido con valiosas sugerencias para abordar el tema desde una perspectiva multidisciplinar y Manuela González Suárez ha sido mi

referente científico en lo que respecta a biología, aportando ideas, revisando los manuscritos y ayudándome pacientemente en la estadística.

El Capítulo 2 es fruto de un trabajo de colaboración con CSIR y CWM (Univ. Pretoria) que realizamos en Sudáfrica en el año 2012. Estoy muy agradecida a Roel Stolper por propiciar esta experiencia y a todos los integrantes del equipo de antifurtivismo de rinocerontes que facilitaron nuestro trabajo en Kwa-Zulu Natal. LD van Essen nos ayudó mucho en el trabajo, respondió a mis infinitas preguntas sobre ecología y rastros de animales africanos, nos acogió en su encantadora casa y nos preparó las mejores braais de carnaza del hemisferio Sur...todo a pesar de que estrellamos el avión en la valla de la granja de su amigo en el primer vuelo de la campaña.

Agradezco a Airam Rodríguez, Jesús Hernández Pliego, Carlos Rodríguez y Javier Bustamante, coautores del artículo del capítulo 3, que me hayan permitido incluirlo en esta tesis, y al LAST-EBD su ayuda en el tratamiento de los datos del mismo.

El apoyo del equipo IREC ha sido fundamental para el desarrollo del capítulo 4. Agradezco muchísimo la paciente dedicación de José Barasona, la amabilidad de Joaquín Vicente y el asesoramiento estadístico de Pelayo Acevedo, además de a todos ellos la fantástica acogida durante mi breve pero intensa estancia en Ciudad Real.

Quiero dar las gracias también a los técnicos que han participado en el trabajo de campo: Luna Puentes hizo un loable esfuerzo para aprender a pilotar UAS; Jorge Gutiérrez adaptó nuestros sistemas a los requerimientos del campo; Esteban Guerrero procesó la mayor parte de los datos y nos proporcionó un montón de emociones con sus despegues únicos; y finalmente a Miguel Ángel Aguilar, el mejor piloto, capaz de encontrar soluciones a cualquier problema técnico y con un sentido del humor gaditano que hizo el trabajo de campo mucho más divertido. Eladio y Javi Martínez (Electronica RC) y Piero (Modelexpert) han sido los proveedores principales de la mayoría de los componentes de UAS, pero también nuestros maestros, asesores y forenses de aviones. Los clubes de radio control Saeta y Bollullos de la Mitación donde realizamos los ensayos antes de volar en los escenarios definitivos también han contribuido al buen desarrollo de este trabajo. Los socios fueron siempre muy amables con nosotros, me dejaban llevar a mi perro Faro al campo de vuelo y algunas mañanas contribuyeron con tortilla, cerveza y chorizo que generosamente compartieron con nosotros. Los voluntarios que han participado en la toma de datos de los experimentos merecen un reconocimiento por su esfuerzo altruista y su

entusiasmo. Recuerdo con especial cariño a Kike Sánchez, Belinda Santos, Paloma y Mari Cuesta.

Parte del trabajo de campo de esta tesis se llevó a cabo en el Parque Nacional de Doñana, gracias al permiso de las autoridades del parque y la colaboración del personal de Reserva Biológica de Doñana. Agradezco especialmente a Fernando Ibáñez y a los guardas su eficaz apoyo logístico. La gente de Palacio y Huerta Tejada hizo que nuestras estancias de campo fueran un placer, especialmente Fabiola con su alegría y Cecilia con sus ocurrencias que me han hecho llorar de risa. También agradezco el trabajo del personal de administración en la Estación Biológica de Doñana que me ayudó con la justificación financiera de los proyectos y otras tareas burocráticas, incluyendo todo lo necesario para que yo cobrara a fin de mes.

Aunque no han participado directamente en este trabajo, José Luis Tellería con sus fantásticas clases en la U. Complutense y las palabras y textos de Miguel Delibes son responsables de mi vocación conservacionista y siempre han constituido una fuente de inspiración.

Miguel Ferrer merece un agradecimiento especial ya que ha influido en mis inicios en la ciencia. Él facilitó mi primera estancia como voluntaria en Doñana, cuando yo aún era una adolescente que dudaba si matricularse en biología o ingeniería aeronáutica. Aquel verano siguiendo águilas calzadas en la marisma como ayudante de Javier Balbontín (que entonces realizaba allí su tesis con Miguel) me convenció de estudiar biología, aunque al final como puede verse, he combinado animales y aparatos voladores. La visión práctica de Miguel acerca del papel del biólogo en la sociedad y su mente abierta a la colaboración multidisciplinar contribuyó sustancialmente al despegue de la aventura UAS.

Toda la línea de investigación de aviones no tripulados para aplicaciones medioambientales no hubiera sido posible sin la participación de Aníbal Ollero, un fantástico ingeniero que a pesar de tener una agenda de locos, encontró el tiempo y las ganas para abordar nuevas ideas y conseguir financiación para llevarlas a cabo.

Como esta tesis recopila parte del trabajo realizado en los últimos años, me gustaría dar unas GRACIAS bien grandes a las personas con las que he compartido este periodo:

A mis compañeros de despacho les agradezco su atención por responder a mis dudas y los buenos ratos que hemos pasado. En particular, siento un especial

cariño y admiración por David Canal, un caballero en una de esas situaciones en las que sólo los que lo son se comportan como tales. A Lorenzo le tocó sentarse a mi lado en un momento complicado, le agradezco sus sabios consejos científicos y el placer de hablar de cosas que no fueran ciencia (y si encuentro el meteorito te doy un trozo).

La vida en la EBD y en la Reserva no hubiera sido igual sin los "cachorros" de las distintas camadas con los que he compartido comidas hablando de temas asquerosillos en el no-comedor, ratos de sol en los escalones, días de playa en el Pichilín, tapeos por Sevilla, anti-mosquitos en la marisma y noches de fiesta y de estrellas en el Palacio. María Viota, Carol, Zulima, Nuno, Irene, Ugo, Letizia, Alessandro, Simone, Fernando, Luis, Alicia, Lidia, Andrea, Chris, Cande, Gemma, Miguel, Laura, Alvarito, Rubén, Pablo y muchos más... Gracias por todos los buenos tiempos.

Mención de gracias especial para mis compañeros del equipo MA: a Marcello D'Amico (así? jeje) por las cuatro mudanzas en las que has cargado mi piano, por creer más en mí que yo y por mostrarme el lado positivo de todo con esa calma espectacular, y para Manuela González por quitarme las garrapatas en la sabana africana, apoyarme y levantarme cuando me he venido abajo, por tu inteligencia, lucidez y bondad y por todo lo que aprendo cada día de ti "queridah amigah".

Miguel Ángel Bravo y Ana Popa, cuántos años y kilómetros recorridos juntos. A los dos, que siempre estáis ahí ¿qué os puedo decir aquí que no sepáis ya? Que os quiero mucho y que ¡me encanta discutir con vosotros!.

Esta etapa andaluza ha sido muy especial gracias a un montón de amigos a los que quiero dar las gracias: a Pablo mi fiel servidor, a Jaume por su infinita capacidad de escucha, a Pedro Luis Mozo por volar conmigo en un coche y regalarme buenos libros, a Isidro por ayudarme a robar el mejor perro de Portugal, a los compis de piso: Emily, Nick, Inés, Ana, Max y Carlo por los buenos ratos en el apartamento más chulo de Triana y a Paco Vega, Matías de las Heras y Andrés de la Cruz por aguantarme más de un berrinche y hacerme reír siempre. Mil gracias también a mi Maestro Antonio Cotán, los dos sabemos que domar un caballo es mucho más complicado que una tesis y gracias a Serengeti por ser tan difícil y mantenernos entretenidos en la tarea.

También quiero dar las gracias a los de siempre, que en esas visitas fugaces casi siempre sin avisar (sorry) me habéis recibido como si no hubiera pasado el tiempo, a los de Madrid: Pati, Irene, Nat, Lorenzana, Elena y Ana; y a los almerienses:

Ana, Carlos y Alfonsito y Andrés. Y como no, a los compañeros con los que he descubierto rincones lejanos: Christian, Mónica, David, Cristina y Adolf, generando recuerdazos (¡¡y los que nos quedan!!).

Por último, precisamente por ser lo más importante, doy las gracias a mi familia, que aunque dispersa geográficamente me ha apoyado en todo: a mi madre, bondad infinita, a mi padre, a mi hermano (love you brother!), a la familia loca-divertida de Barcelona, a mi abuela que debería ser científica, a mi abuelo que hubiera disfrutado mucho de esta tesis y a Carmen y Jacinto que también son familia. Y también a Faro, mi mejor amigo, que siempre estuvo a mi lado.

¡Gracias a todos!

This Ph.D. thesis attempts to fill the gap of knowledge in the use of UAS in conservation biology. It describes for the first time the use of these systems in an immediately applicable way in impact assessment of infrastructures for wildlife, and for the protection of endangered species. Furthermore, it presents UAS as a tool for obtaining high-resolution spatiotemporal information, which helps to understand animal habitat use in rapidly changing human dominated areas. It also demonstrates that these systems are able to provide information as valid as the obtained by conventional techniques on the spatial distribution of species in protected areas.

