Universidade de Évora - Escola de Ciências e Tecnologia

Mestrado em Biologia da Conservação

Dissertação

Interspecific variation in avoidance behaviour of soaring migrating birds in wind farms: the case study of Barão de São João (Algarve, Portugal)

Patrícia Isabel Cavaco Cota Paussão Nabo

Orientador(es) | Ricardo José Azul Baptista Martins Tomé
João Tiago Sabino Lino Marques
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Table of Contents

List of abbreviations and acronyms

List of figures

List of tables

Resumo

Variação interespecífica de comportamentos de evitamento de aves planadoras migradoras em parques eólicos: o caso de estudo de Barão de São João (Algarve, Portugal)

Os parques eólicos estão associados a impactos em diferentes grupos de animais e as aves planadoras são um dos mais afetados. Neste estudo avaliamos diferenças interespecíficas no comportamento de evitamento de aves planadoras migradoras ao cruzarem um parque eólico no Sudoeste de Portugal. Analisámos alterações de distância às turbinas e na sinuosidade dos movimentos, comparando entre períodos antes e após a construção do parque eólico. Para além de diferenças entre espécies examinámos também diferenças no uso de diferentes classes de altura. Os resultados revelam que, após a construção, (1) os movimentos das aves são mais sinuosos, (2) algumas espécies privilegiam voos acima das turbinas, (3) bandos de águias-calçadas voam a maiores distâncias do parque e (4) os abutres não demonstram evitamento. Este estudo evidencia respostas de evitamento das turbinas por parte das aves, os quais podem resultar em gastos energéticos adicionais que poderão afetar o sucesso da migração. Isto pode servir de base para a definição de medidas de mitigação em parques eólicos diferenciadas ao nível da espécie.

Abstract

Wind farms are associated with impacts on different animal groups and soaring birds are one of the most affected. In this study, we assess interspecific differences in avoidance behaviours of migratory soaring bird species while crossing a windfarm in southwestern Portugal. We analysed changes in movements' distance to turbines and linearity, comparing between periods before and after the windfarm implementation. Beside differences between species, we also examined differences in the use of height classes. The results reveal that after the construction of the wind farm (1) birds' movements are more sinuous, (2) some species favour flights above the turbines, (3) flocks of Booted Eagles fly at greater distances from turbines and (4) vultures show no avoidance responses. Our study highlights the existence of bird avoidance responses to wind turbines, which may result in additional energy demands that might affect the migration success. This may be used as a base to define mitigation measures in windfarms at a species level.

1. Introduction

1.1. Impacts of wind farms on birds

Concern for the environmental crisis and the need to reduce greenhouse gas emissions has increased in the last decades, so the role of renewable energies in this matter has gained weight. Wind energy is one of the types that has grown faster worldwide (IRENA, 2019) and the development of this technology in Portugal has also been notable (APREN & INEGI, 2018). However, this type of "green energy" has faced some controversy, since it is known to cause impacts, particularly mortality, on several groups of animals (Arnett *et al.*, 2016; Sirén, *et al.*, 2017; Smallwood, 2013).

Birds are one of groups most affected by wind farms, since these may cause fatal and non-fatal collisions, habitat loss due to disturbance, habitat modifications and barriers to movements (Drewitt & Langston, 2006, 2008; Garvin *et al.*, 2011; Keil & Otter, 2005; Marques *et al.*, 2014; Scottish Natural Heritage, 2009; R. T. Watson *et al.*, 2018). How wind farms and associated structures impact birds will depend on several factors and these can be site-specific, such as weather, location, topography or wind farm layout, and species-specific flight type, morphology, social behaviour or vision field (Barrios & Rodríguez, 2004; Blumstein *et al.*, 2005; Cabrera-Cruz & Villegas-Patraca, 2016; Dahl *et al.*, 2013; de Lucas *et al.*, 2004; Drewitt & Langston, 2006; Marques *et al.*, 2014; Martin, 2010; Smallwood *et al.* 2009; Villegas-Patraca, Cabrera-Cruz, & Herrera-Alsina, 2014).

Soaring birds, especially raptors, are particularly impacted by wind farms due to their characteristics and flight behaviour (Barrios & Rodríguez, 2004; Garvin *et al.*, 2011; Marques *et al.*, 2014; Péron *et al.*, 2017; R. T. Watson *et al.*, 2018). Most soaring birds are species with long longevity, late maturity, low reproduction rates and that are often of conservation concern, therefore the added mortality of collisions with wind turbines or other impacts that are associated with wind farms may represent worrying effects on populations that are already sensible (Carrete *et al.*, 2009; Drewitt & Langston, 2006, 2008; Garvin *et al.*, 2011; Martínez-Abraín *et al.*, 2012; J. W. Watson *et al.*, 2018; R. T. Watson *et al.*, 2018).

Raptors and other soaring birds have generally medium to large body size and broad wings, which means that flapping flight has a high energy cost. Thus, most of their main flight types are thermal soaring, or orographic lift, intercalated with gliding (Agostini *et al.*, 2015; Dahl *et al.*, 2013; Duriez *et al.*, 2014; Miller *et al.*, 2014; Rayner, 1988; Videler, 2006). Thermals are ascending columns of air formed when the ground heated by the sun warms the air around it, which becomes warmer than its surroundings, and consequently raises. Birds use these columns to circle upwards and gain flight altitude, before gliding onto the next thermal (Angevine, 2006; Videler, 2006). Soaring birds also make use of other types of ascending columns of air such as the orographic lift, upward currents formed from deflected air along mountainous terrains such as ridges, coasts and hills (Johnston *et al.*, 2014). The areas were orographic lifts are formed are also good locations for the implementation of wind farms due to the potential of energy production (Barrios & Rodríguez, 2004; Pearce-Higgins, Stephen, Langston, Bainbridge, & Bullman, 2009), which means that these can be areas where birds and wind turbines intersect, representing a great risk of collision for birds. If aside the turbine's interception, these are also areas regularly used by many soaring birds like migratory flyways, then these birds can face an even greater risk (Drewitt & Langston, 2006, 2008; Marques *et al.*, 2014; Masden *et al.*, 2009). Therefore, areas with high bird abundance combined with other factors may increase collision risk and mortality (Carrete *et al.*, 2012; Drewitt & Langston, 2006), but the effect of abundance is not consensual, since de Lucas *et al.* (2008) considers that collision risk does not depend on bird abundance.

Weather, and especially wind conditions, is also among the main factors that influence collision risk. In fact, some studies have shown that birds are more active at low wind speed (Barrios & Rodríguez, 2004; May *et al.*, 2015). On the other side, strong winds (*i.e.* high wind speed) may be problematic for birds because they reduce the availability and creation of thermals, leading birds to rely mostly upon orographic lift (Johnston *et al.*, 2014). As mentioned above, the type of terrains were these lifts are formed is associated with high collision risk, since they are often also favourable for wind energy production. Moreover, birds that fly against strong headwinds tend to reduce flight altitude, which can place them at turbines' height (Johnston *et al.*, 2014; R. T.

Watson *et al.*, 2018). Strong headwinds may even reduce birds flight speed, implying a greater risk of collision with turbines blades that are rotating at high speeds (Jenkins *et al.*, 2018). Very low wind speeds may also increase the collision risk for soaring birds, since thermal formations will be weaker, resulting in poor lifts for the birds (Barrios & Rodríguez, 2004; R. T. Watson *et al.*, 2018).

Therefore, the implementation of adequate mitigation measures that can avoid or reduce impacts of wind farms on birds is very important (de Lucas *et al.*, 2012; Marques *et al.*, 2014; Pescador *et al.*, 2019), especially the suitable setting of wind farms (R. T. Watson *et al.*, 2018). For this, pre-construction and post-construction studies are needed in order a better understanding of the risks and possible implementation of mitigation measures.

1.2. Avoidance behaviour

Collision mortality is one of the most studied impacts of wind farms on birds and is considered one of the most important (Barrios & Rodríguez, 2004; Carrete *et al.*, 2009, 2012; Dahl *et al.*, 2013; de Lucas *et al.*, 2012, 2008; Drewitt & Langston, 2008; R. T. Watson *et al.*, 2018). Yet, displacement and barrier-effects can also be impacting since the first may result in habitat loss in the long-term and the other may imply an increased use of energy that can be essential to migration (Desholm & Kahlert, 2005; Drewitt & Langston, 2006; Garvin *et al.*, 2011; Pearce-Higgins *et al.*, 2009). Both displacement and barrier-effects result from avoidance behaviours.

Avoidance behaviours can be divided in three main categories: macro-avoidance, if the birds avoid the whole wind farm; meso-avoidance, when birds cross the wind farm, but still avoid the turbines; micro-avoidance, when birds avoid imminent collision or if they pass through the rotor swept zone (Cook *et al.*, 2014). May (2015) makes an interesting analogy: he considers macro-avoidance as avoiding a “forest”, meso-avoidance as avoiding the “trees” and micro-avoidance as avoiding the “branches”.

How birds react to an obstacle, showing avoidance or not, may depend on species-specific characteristics. While some species may prefer horizontal avoidance by changing their flight trajectory or direction of travel, others can increase flight altitude, displaying vertical avoidance, and some might even use both types of behaviour (Cook *et al.*, 2014; Johnston *et al.*, 2014; Plonczkier & Simms, 2012). It may also differ with social behaviour, as Garvin *et al.* (2011) found that individual raptors tended to fly on a straight trajectory through the wind farm, while other studies reveal that flocks tend to avoid turbines, albeit small flocks may behave similarly to individual birds due to having greater manoeuvrability than large flocks (Croft *et al.*, 2015; Desholm & Kahlert, 2005).

The ability of a bird to avoid obstacles such as turbines will also depend greatly on manoeuvrability and capacity of powered flight, which depend on wing loading, *i.e.* body weight divided by wing area, and aspect ratio— squared wingspan divided by wing area (Agostini *et al.*, 2015; de Lucas *et al.*, 2008; Janss, 2000; Newton, 2008). According to Rayner (1988), low wing loading (WL) is associated with high manoeuvrability, while high aspect ratio (AR) reflects lower flight costs. This author classifies bird groups into categories depending on WL and AR, where thermal soarers (*e.g.* storks, vultures, eagles, buzzards) are birds with low WL and low AR. Lower WL will allow birds to have a better ascending capacity in thermals and this may compensate the higher flight costs these species have due to low AR; but due to soaring flight type they also have a decreased manoeuvrability and are very dependent of wind conditions (Shamoun-Baranes *et al.*, 2009).

1.3. The case study of Barão de São João

As mentioned before, soaring birds rely mainly on thermal soaring as flight type, since flapping costs a lot of energy to them. This is especially important during migrations, since birds have to fly for long distances and soaring allows them a low energy cost flight, but thermals are weaker over the sea and soaring birds that make inter-continental migrations seek to cross where water extensions are narrower (Newton, 2008; Pennycuick, 2008; Rayner, 1988). The Strait of Gibraltar is an important migration flyway for hundreds of thousands soaring birds across central and north-western Europe that migrate to Africa in autumn and return in the spring (Barrios & Rodríguez, 2004; de Lucas *et al.*, 2004; Newton, 2008). However, some migrants carry out a deviation from the main route and end up in the peninsula of Sagres, in the south-westernmost point of Portugal. These birds may be disoriented or were dragged by strong east winds, moreover most are juveniles on their first migration that may be lost due to inexperience. Sagres works as a dead-end for migratory soaring bird species because these birds cannot cross from this point to Africa (like passerines do) so these birds agglomerate in the area before changing their flight course. Due to its location, the region of Sagres is a very important flyway for migrating soaring birds and other bird species (Canário *et al.*, 2012; Tomé *et al.*, 2017).

The Barão de São João wind farm, hereafter termed BSJWF, is located close to Sagres, in a forested area where 25 wind turbines are set along two ridges. Also, the BSJWF is located partly in the Site of Community Importance (SIC) of Costa Sudoeste, due to the presence of habitats included in the Annex I of the Directive 92/43 (Directive Habitats), as well as fauna and flora species in the Annex II (STRIX, 2016). Therefore, the area was studied in a pre-construction phase in order to detect potential risks for birds. A great transit of migrating soaring birds was detected and thus monitoring and mitigation programs have been in place since 2010. The entity responsible for the pre-construction study and implementation of monitoring and mitigation measures during post-construction is STRIX.

STRIX is a company that provides environmental, social and sustainability consultancy, as well as technical assistance services and products, being active since 2001 (STRIX, 2017). This company has been studying BSJWF since 2004 and is still monitoring the area, as part of the mitigation programs (STRIX, 2016).

Monitoring is conducted by observers from vantage points (VPs) located inside and outside of the wind farm (Fig. 1). One of these VPs has a x-band radar operating at a horizontal range of 8 km. The observers are responsible for the detection of birds and to analyse the need to apply the mitigation measure RASOD (Radar Assisted Shutdown of Turbines). Upon detection of birds at risk, the observers warn the fieldwork team coordinator who must decide if the turbines should be shutdown. To support this decision, the team follows certain criteria that if verified


Figure 1: Example of monitoring in the BSJWF.

entails the shutting down of turbines. These criteria encompass the detection of: (i) an intense migratory flux of soaring birds; (ii) flocks of migrating soaring birds near BSJWF or approaching it in flight heights that imply risk of collision; (iii) threatened soaring bird species (*e.g. Ciconia nigra*) near the wind farm or approaching it at risky flight altitudes. If none of the previous criteria is met, the coordinator may still order shutdown of turbines if there are migratory soaring birds in imminent risk of collision (STRIX, 2016; Tomé *et al.*, 2017).

Using movements data of the BSJWF provided by STRIX and considering the previously mentioned sensitivity of migrating soaring birds to wind farms, the main objectives of this study are (1) to analyse if five species of this group that crossed the BSJWF reacted to it after its construction and (2) if there are interspecific differences in avoidance behaviours and how will these differences manifest in each species.

1.4. Studied species

Among the five species of migrating soaring birds considered in this study, there are four species of raptors, *i.e.* Booted Eagle (*Hieraaetus pennatus*), Egyptian Vulture (*Neophron percnopterus*), European Honey Buzzard (*Pernis apivorus*) and Griffon Vulture (*Gyps fulvus*), and the Black Stork (*Ciconia nigra*).

The Booted Eagle is a summer visitor that winters in Africa and its presence in Europe during winter is very exceptional. It is mainly a solitary bird, only hunting alone or in pairs (ICNB, 2008) and its conservation status is least concern (LC) in Europe (IUCN, 2019) and near threatened (NT) in Portugal (Cabral *et al.*, 2005).

The Egyptian Vulture is a summer visitor that breeds in some parts of southern Europe (including Portugal) before migrating to wintering areas in Africa (ICNB, 2008). The Egyptian vulture is an endangered (EN) species globally (IUCN, 2019) and in Portugal (Cabral *et al.*, 2005).

The Honey Buzzard is also a summer visitor that nests in Europe, but winters in Africa. Although solitary while foraging, forms big flocks during migration and in roosting spots (ICNB, 2008). Although its conservation status is LC in Europe (IUCN, 2019), in Portugal is considered as vulnerable (VU) (Cabral *et al.*, 2005).

The largest species of the group is the Griffon Vulture, a colonial resident bird that nests in Europe, although some individuals migrate to Africa in post-nuptial movements, especially juveniles (ICNB, 2008). The species is considered as LC in Europe (IUCN, 2019) and NT in Portugal (Cabral *et al.*, 2005).

Finally, the Black Stork is another summer visitor that nests in the Iberian Peninsula, central Europe and till eastern Siberia, wintering in Africa, Pakistan and China. During breeding the species is found in pairs (ICNB, 2008), but STRIX has records of migrating flocks. Its conservation status is LC in Europe (IUCN, 2019) and VU in Portugal (Cabral *et al.*, 2005).

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2. Research article

Interspecific variation in avoidance behaviour of migratory soaring birds in wind farms

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2.1. Abstract

Wind power technology is a prominent source of renewable energy and is growing worldwide. However, windfarms can cause several impacts on birds and other groups of fauna, with soaring birds standing out as one of the most affected. We studied avoidance behaviours of five species of migratory soaring birds that crossed over the study area before and after the construction of the Barão de São João wind farm, located in a region of intense migratory flow and in Site of Community Importance (SCI) of SW Portugal. We focused our study on Black Stork *Ciconia nigra*, Booted Eagle *Hieraaetus pennatus*, Egyptian Vulture *Neophron percnopterus*, Griffon Vulture *Gyps fulvus* and the European Honey Buzzard *Pernis apivorus*. We analysed changes in distance to turbines and linearity between before and after construction periods and species, comparing differences in flight altitude and flocking behaviour, and assessing the possible effect of wind variables. Our results show the existence of differences in behaviour among species and particularly in flocking behaviour, flocks of Booted Eagles fly at greater distances from turbines after the construction. Most species also show more sinuous movements in post-construction, some also increased their flight altitude above the turbines (*i.e.* Black Storks, Booted Eagles and Honey Buzzards) and even fly at greater distances from turbines at blades range altitudes (*i.e.* risk classes). However, both vulture species lacked clear avoidance responses. Differences between pre- and post-construction periods were also found in wind direction, however wind speed and flight direction did not show differences; the main directions of flight and wind direction also indicate that birds flew mostly in crosswinds, so wind conditions probably did not affect flight manoeuvrability. This study shows avoidance behaviours of migratory soaring birds that crossed the windfarm which may have consequences because changes in the trajectory of movements result in additional energy expenditure that might be crucial for long-distance migrating birds.

Key-words: windfarms, avoidance, flight altitude, barrier-effect, multi-species, linearity.

2.2. Introduction

In the last decades, wind power technology has been developing at a fast pace and so have the number of wind farms around the world (IRENA, 2019). Although renewable energies are important to reduce the emission of greenhouse gases, wind farms are also associated with impacts to birds. Some of the main impacts involve fatal and non-fatal collisions with wind turbines, habitat modifications, habitat loss due to disturbance and barrier-effect (Drewitt & Langston, 2006, 2008; Garvin *et al.*, 2011; Keil & Otter, 2005; Marques *et al.*, 2014; Scottish Natural Heritage, 2009; R. T. Watson *et al.*, 2018). The effects of these impacts will depend on site-specific (*e.g.* weather, topography, wind farm layout, location) and species-specific factors (*e.g.* morphology, flight type, vision fields, social behaviour) (Barrios & Rodríguez, 2004; Blumstein *et al.*, 2005; Cabrera-Cruz & Villegas-Patraca, 2016; Dahl *et al.*, 2013; de Lucas *et al.*, 2004; Drewitt & Langston, 2006; Marques *et al.*, 2014; Martin, 2010; Smallwood *et al.*, 2009; Villegas-Patraca *et al.*, 2014).

Avoidance behaviour is an important factor to consider concerning the impacts of wind farms, as a strong display of it may result in displacement and consequent habitat loss (Garvin *et al.*, 2011; Kelsey, Felis, Czapanskiy, Pereksta, & Adams, 2018; Pearce-Higgins *et al.*, 2009), or barrier-effects that will result in increasing energy consumption when birds change their trajectory (Desholm & Kahlert, 2005; Masden *et al.*, 2009), while last minute reactions to turbines or even a lack of avoidance responses may mean that birds are more prone to collisions (Dahl *et al.*, 2013; Krijgsveld, 2014). This behaviour can be divided into three types: micro-avoidance, meso-avoidance and macro-avoidance (Cook *et al.*, 2014; May, 2015).

Soaring birds are particularly affected by wind farms. Their powered flight have a high energy cost due to their body size and wing characteristics, so they rely mostly on thermals or orographic lifts to gain altitude (Agostini *et al.*, 2015; Dahl *et al.*, 2013; Duriez *et al.*, 2014; Miller *et al.*, 2014) and since wind farms are often located in landscape features that meet these conditions (*e.g.* ridges, coastlines, hills) birds and wind turbines will often intersect, which amplifies the risk of collision (Barrios & Rodríguez, 2004; Pearce-Higgins *et al.*, 2009). The fact that most species of soaring birds have a great longevity, late maturity and low reproduction rates reinforce the pressure that wind farms may present to populations of soaring birds, especially in species of conservation concern (Carrete *et al.*, 2010; Drewitt & Langston, 2006; Garvin *et al.*, 2011; Martínez-Abraín *et al.*, 2012; R. T. Watson *et al.*, 2018). Therefore, a good placement of turbines and implementation of mitigation measures are important, mainly in areas with intense bird movement such as breeding grounds and migratory flyways (Drewitt & Langston, 2006, 2008).

The Strait of Gibraltar is one of the most important flyways for European migratory soaring birds, as hundreds of thousands of birds from the Iberian Peninsula and from central and north-western Europe will cross this region during their migration to Africa (Barrios & Rodríguez, 2004; de Lucas *et al.*, 2004; Newton, 2008). A portion of these birds deviate from this route and end up in Sagres, in SW Portugal, which works as a dead-end and an agglomeration area for migratory soaring species. Since these birds cannot cross to Africa from this point, they have to correct their course and return to Gibraltar on a SE route (Canário *et al.*, 2012; Tomé *et al.*, 2017).

In the area of Sagres, the number of implemented wind farms has been increasing (APREN & INEGI, 2018). Although documented, there is a need for studies that compare the impact of wind farms on birds between pre- and post-construction periods. In most studies there is a lack of information or data collection prior to the building of the wind farm (Carrete *et al.*, 2010; Janss *et al.*, 2010; Jenkins *et al.*, 2018; Scottish Natural Heritage, 2009; Villegas-Patraca *et al.*, 2014). This need is especially important for soaring birds, since even though comparisons have been made, namely regarding collision risk and mortality (Barrios & Rodríguez, 2004; Cabrera-Cruz & Villegas-Patraca, 2016; de Lucas *et al.*, 2004; Pearce-Higgins *et al.*, 2012; Péron *et al.*, 2017), comparisons between migratory soaring species are lacking, particularly endangered species (Carrete *et al.*, 2009). Additionally, to our knowledge few studies have so far analysed vertical and horizontal avoidance in soaring birds (de Lucas *et al.*, 2004; Garvin *et al.*, 2011; Marques *et al.*, 2019; J. W. Watson *et al.*, 2018), or seeking for differences between individuals and flocks (Croft *et al.*, 2015; Desholm & Kahlert, 2005; Garvin *et al.*, 2011; Plonczkier & Simms, 2012).

In this study we aim to compare differences in reaction to a wind farm in the area of Sagres of five species of migrating soaring birds during pre- and post-construction. We chose species with different wing loading and aspect ratio, since these are known for affecting the bird's ability to avoid obstacles (Agostini *et al.*, 2015; de Lucas *et al.*, 2008; Janss, 2000; Newton, 2008; Rayner, 1988) and, therefore, we expect to observe differences in behaviours among species. Our studied species are the Black Stork, Booted Eagle, Egyptian Vulture, Honey Buzzard and Griffon Vulture. Most of these birds are long-distance migrants with Griffon Vulture being the only exception because the species is mainly resident in Portugal, although some birds (mostly juveniles) migrate to Africa in late summer and autumn movements (ICNB, 2008; STRIX, 2016).

We aimed to assess (1) if there is a horizontal avoidance of turbines and linearity changes between species and construction periods, (2) if there are differences between height classes (vertical avoidance) and (3) if flocking influences movements' distance to turbines and linearity. We hypothesised that birds with lower wing loading would show more avoidance than other species by flying at greater distances to turbines or increasing flight height and that flocks would also avoid more the turbines than individual birds.

2.3. Methods

2.3.1. Study Area

We conducted our study at the Barão de São João wind farm (hereafter BSJWF), which is located close to the village of Barão de S. João (Lagos, Algarve, Portugal) ca. 25 km away from Sagres and the St. Vincente Cape, the most southwestern point of Portugal and mainland Europe (37° 08’N and 8° 48’W; Fig. 2). Due to its location, BSJWF is traversed by one of the main migration routes for birds of prey travelling to Africa. The implementation area of the wind farm is also partly located in a Site of Community Importance (SCI) denominated as Costa Sudoeste (STRIX, 2016).

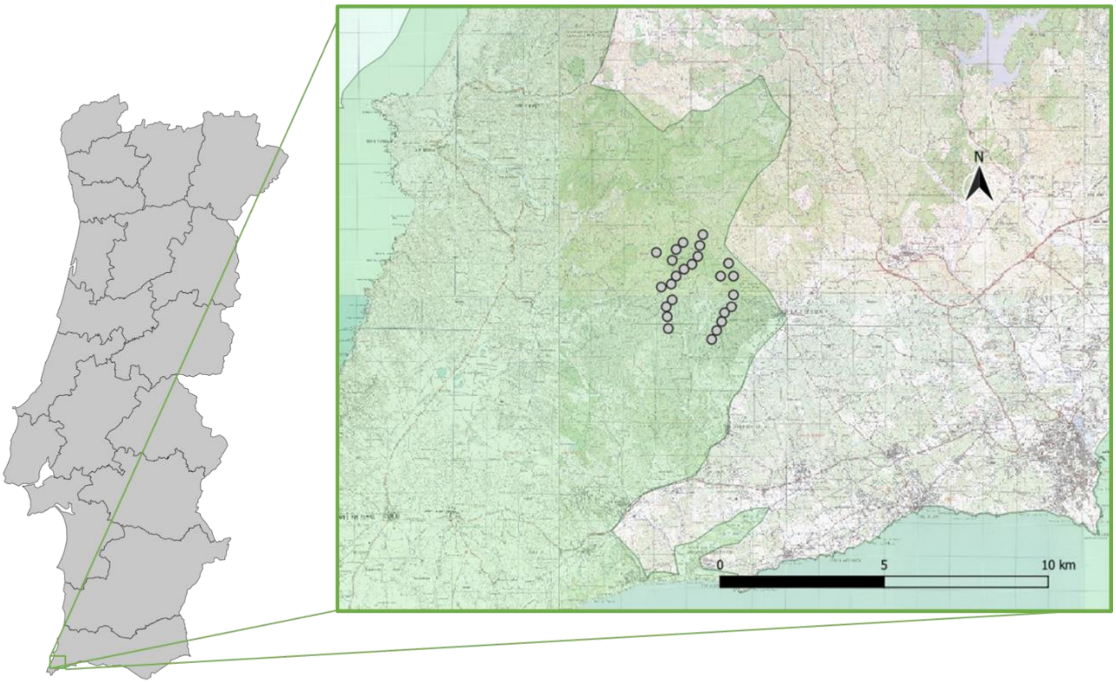

Figure 2: Location of the BSJWF within Portugal and map showing its wind turbines (grey dots). The green shaded area shows the Natura 2000 SCI Costa Sudoeste.

BSJWF includes 25 turbines with an installed capacity of 50MW (2MW per turbine; Fig. 2). Turbines are installed along two ridges oriented NNE-SSW (max. height = 158m for the western ridge and 177m for the eastern) separated by a valley (min. height = 73m); minimal distance between turbines of different ridges is 921m, and distance between turbines ranges from 273m to 539m. Each turbine is composed by one nacelle placed at 80m high and three blades (45 m long) that rotate from 35m to 125m above the ground (Fig. 3).

The area is mostly occupied by forest plantations of *Eucalyptus* sp., recreational forest (Mata Nacional do Barão de S. João, mostly Stone Pine *Pinus pinea*) and scrubland (mostly Gum Cistus/Rock Rose *Cistus ladanifer*).

Figure 3: Turbines at the BSJWF, showing the nacelle height and minimum and maximum heights reached by the blades.

2.3.2. Field work

Monitoring of soaring birds during fall migration started in 2004 due to wind farm's Environmental Impact Assessment (EIA) and is still taking place nowadays (STRIX, 2016). Before the construction of BSJWF (in 2008) monitoring was conducted in 2004, 2005 and 2007, and from 2008 onwards the monitoring scheme has been conducted yearly. For our study we used data from the three years of pre-construction and three of the most recent years from post-construction series: 2015, 2016 and 2017 (results from 2018 and 2019 were not available yet when we started this study).

In each year, monitoring takes place from mid-August to late November. In the pre-construction phase, it was carried out for 2-3 weeks each month (30 days average of monitoring per year); during post-construction it is continuous on a daily basis with a total of 108 days of monitoring per year.

Monitoring is conducted every day from 9 am to 6 pm by observers equipped with binoculars and telescope (Fig. 1), detecting and tracking bird movements in the BSJWF area from vantage points (VPs), with one observer per VP. In the pre-construction phase two VPs were set within the windfarm perimeter (WPs), while the observation and tracking network was expanded in the post-construction by adding five extra VPs within a security perimeter (SPs) ranging from approximately 1.5km to 4.5km around the wind farm (Fig. 4). SPs were established aiming for an earlier detection of soaring birds in order to avoid collisions by applying a RASOD (Radar Assisted Shutdown of Turbines) mitigation procedure. The decision to shutdown the turbines is made by a field coordinator and this decision is supported by certain criteria (*e.g.* eminent risk of collision, approach of a flock) that if verified entails application of the measure. In one of the SPs (SP1) an X-band marine radar operated on horizontal mode with a range of 6 to 8km to help timely bird detection (STRIX, 2016).

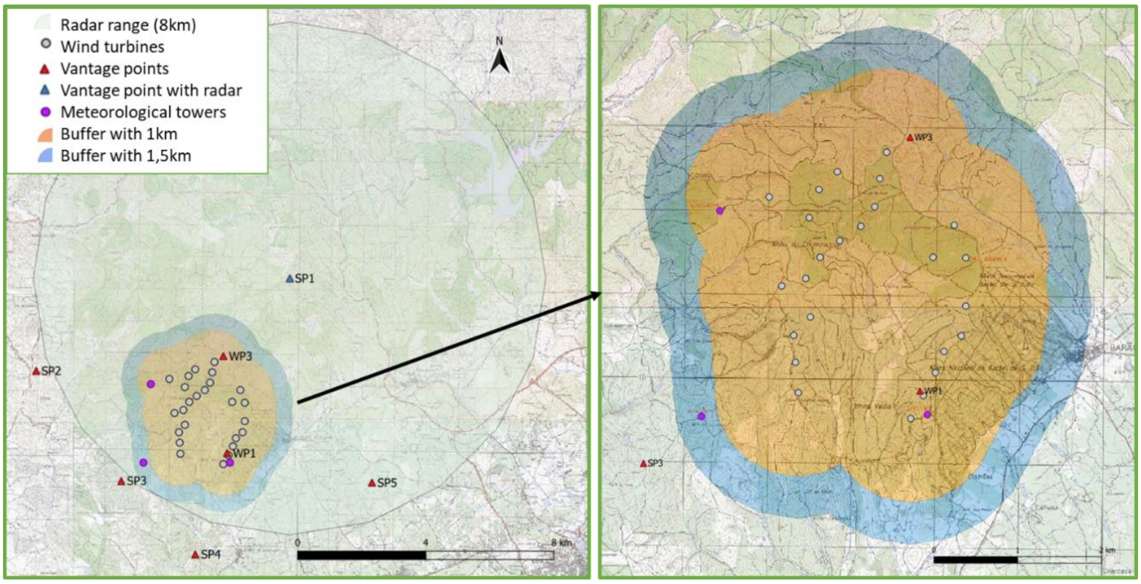

Figure 4: Location and spatial arrangement of BSJWF wind farm. Vantage points (VPs) within (WPs) and around (SPs), radar location and radar's range when set at 8km are represented. The 1km buffer (orange) and the 1.5km buffer (blue) around the turbines used for analysis are also represented.

In each VP the observers mapped all soaring bird movements by drawing accurately the trajectories birds took while noting down changes in flight altitude and where they occurred spatially. Each used map was numbered and identified with the observer's name, vantage point and date. Each drawn movement was identified by an individual number and its associated information (species, number of birds, age, sex, time, height class, type of movement and behaviour) was registered on a field spreadsheet. Spreadsheets also included information on the starting and ending times of the monitoring work and on any forced interruptions (*e.g.* due to inclement weather).

Distinction of used flight height classes (<20m; 20-60m; 60-100m; 100-200m; 200-500m and >500m) was visually done by observers, using some guiding landscape cues in the area like known heights of trees, the three meteorological towers (max. height = 80m) and the wind turbines (Fig. 4).

2.3.3. Specie's selection

From a total of more than 30 soaring bird species in the full dataset of STRIX, we selected the following five species: Griffon Vulture, Egyptian Vulture, Booted Eagle, Honey Buzzard and Black Stork. This selection was based on (1) the amount of data available, (2) their body size, (3) conservation status and (4) their vulnerability to wind farms (Table 1).

Table 1: Details of body mass, wing loading and aspect ratio (Agostini et al., 2015; Bruderer & Boldt, 2001), of conservation status in Portugal (Cabral et al., 2005), conservation status in Europe (IUCN, 2019) and annual averages of number of birds estimates recorded at BSJWF for each species between 2009 and 2018 (STRIX unpub. data).

Species	Body mass (kg)	Wing loading	Aspect ratio	Conservation status (Portugal)	Conservation status (Europe)	Annual average nr. of birds
Black Stork	3.00	10.56	7.92	VU	LC	50
Booted Eagle	0.74	3.68	7.69	NT	LC	426
Egyptian Vulture	1.90	5.34	7.89	EN	EN	60
Griffon Vulture	6.80	6.87	6.52	NT	LC	2241
Honey Buzzard	0.79	3.35	7.16	VU	LC	116

Body mass (BM; body weight), wing loading (WL; body weight divided by wing area) and aspect ratio (AR; squared wingspan divided by wing area) are important biological traits to consider for wing loading collision risk and avoidance behaviour, because they are a proxy of birds' flight action and manoeuvrability (Agostini et al., 2015; Duriez et al., 2014; Greenewalt, 1975; Pennycuick, 2008) and hence their avoidance ability (Blumstein *et al.*, 2005; Garvin *et al.*, 2011).

2.3.4. Movements selection and representation

We selected 30 movements per construction period for each species (*i.e.*, a total of 60 movements for each species) to analyse differences in bird's behaviour after the construction of the wind farm. Selected movements were depicted as georeferenced lines using QGis, version 3.2.1-Bonn (QGIS Development Team, 2018).

Most selected movements had been registered in the WPs although complementary information from the SPs regarding those movements was also used when available for the post-construction phase. As observers in those VPs could detect birds before reaching the wind farm, information from SPs often complemented that from WPs in relation to length, height classes, etc. Likewise, information from the two WPs and/or different SPs was merged whenever possible to achieve the most complete and trustable portrait of each observed movement.

Whenever possible, each bird movement was continuously followed by an observer from the moment of detection. If at some point the observer could not follow it properly, another observer from the closest VP carries on with the observation and successively through other VPs. Therefore, this may result in spatial and time gaps between records of different VPs. So, the drawn movements were carefully examined and only merged if, considering the time of record and the trajectory, there were no doubts it was the same movement. This way, if there was a gap between the mapped representations of the same movement by different VPs, we only merged them when the trajectory was approximately linear in the separation zone and if the gap's length was less than 250m.

The selection of the 30 movements/species/construction period was based on the following criteria: (i) trajectories that crossed the wind farm, that were detected before incoming, in and outgoing the wind farm; (ii) movements of considerable length that were drawn only entering or only leaving the wind farm, but always crossing part of the wind farm; (iii) and trajectories of considerable length that while not entering the BSJWF perimeter, clearly approached the turbines.

With the application of the criteria explained above 30 movements could be considered for each selected species for the post-construction phase. However, in the case of the Black Stork and Egyptian Vulture, respectively only nine and eight pre-construction movements were considered as eligible for the pre-construction phase (Table 2, Annex). Due to additional information from SPs, post-construction movements had greater lengths than pre-construction movements. Thus, the selected movements were cut by buffers of 1 and 1,5km with QGis tools to reduce this variation in length.

2.3.5. Data analyses

In this study we entirely focused on meso-avoidance by soaring birds, *i.e.*, the reactions of birds approaching wind turbines within a wind farm.

2.3.5.1. Distance to turbines

To analyse the trajectories' distances to turbines, we calculated the minimal distances from each bird trajectory to each wind turbine, which resulted in 25 distances per movement. From these, we selected the five lowest measurements for each movement, which were compared between construction periods and species.

2.3.5.2. Differences in flight altitude

We recorded flight altitude data into 6 height categories (<20m, 20-60m, 60-100m, 100-200m, 200-500m, >500m) (STRIX, 2016; Tomé *et al.*, 2017) to analyse differences between construction periods and species. According to this classification the height categories 20-60m, 60-100m and 100-200m present a collision risk, since the turbine blades reach this interval (Fig. 2).

In analyses with height classes, we calculated the five minimum distances to wind turbines for each height category of each movement.

We also analysed the change in the proportion of movements for each height class between construction periods. To obtain the proportions, we computed the number of movements with at least one section registered in a given height class, for each construction period and for each species and divided it by the total number of movements for that species in that construction period. Then, we obtained the difference in movement proportion between construction periods, for each height class of each species by following formula:

$$\frac{\text{Post} - \text{Pre}}{\text{Pre}} \times 100$$

2.3.5.3. Effects of flocking in movement patterns

To analyse the differences in behaviour of individuals and flocks' in response to the wind farm (distances to turbines and linearity), we divided movements according to the number of birds involved (Table 7, Annex).

While dividing movements into flock classes, we were faced with constraints in the number of movements of individuals and flocks, so species have different classes (Table 7, Annex). For each species, if movements of flocks were more numerous than movements of individuals, we divided movements with two or more birds into different classes according to the number of birds involved and assuring a similar number of movements per flock class, in order to dilute the differences between individuals and flocks and reduce their effect on results. If movements of individuals were more than movements of flocks, all movements with two or more birds were joined in a single class.

2.3.5.4. Flight linearity

One of the behavioural response of birds to new structures can be the decrease in the movement linearity because birds in unfamiliar areas with a high number of obstacles may change their flight pattern to a more sinuous one. We estimated the linearity of each trajectory by calculating the ratio between the length of a straight line connecting the initial and final tips of a recorded (drawn) movement and the movement real total length. Thus, straight trajectories have values close to 1 while very sinuous, almost circular trajectories have values close to 0. We analysed differences in linearity between construction periods and species for the whole set of movements but also according to the flock classes described above.

2.3.5.5. Effect of wind and flight direction

One of the factors known to affect birds' collision risk is wind. Collision risk increases with wind speed, since the availability of thermals is reduced in strong wind, while in terms of direction headwinds and tailwinds seem to be riskier than crosswinds, as birds reduce flight altitude in these conditions (Johnston et al., 2014; R. T. Watson et al., 2018). Therefore, wind speed and wind direction were included in the analyses, so that we could better understand how these meteorological factors might have affected the birds' behaviour.

We used data on wind speed (m/s) and wind direction (degrees) from three meteorological towers located at BSJWF (Fig. 5) that record weather data almost continuously (in 10min intervals). However, data from 2007 could not be retrieved and therefore data collected by field observers was used as a surrogate (Fig. 5). These field data was collected three times a day: at the start, middle and end of monitoring. Wind direction was recorded as the initials of cardinal, intercardinal or secondary intercardinal directions, so we converted it in degrees for analyses, while wind speed was recorded in Beaufort classes, so we had to the convert it to the mean value of the class.

Figure 5: Example of wind speed sampling in Cabranosa (Sagres). A similar procedure was used in field data sampling at BSJWF in 2007.

The data from the meteorological towers is collected at an altitude of 80m, while data from the observers is collected at a maximum of 2,5m. Therefore, we compared data from 2016 between these two sources and obtained notable differences in wind speed. To correct this issue, we used the wind speed data from 2016 to obtain a regression line between data from the towers and observers (correlation coefficient =

0.71; $R^2 = 0.50$), and applied the resulting equation ($y = 0.8518\,x + 3.7903$) to wind speed data from 2007.

The movements flight directions were obtained by the difference between the angle at the start of the movement and the angle at the end of the movement.

2.3.5.6. Statistical Analysis

All statistical analyses were done in R (R Core Team, 2017), with RStudio as an integrated development environment (IDE) (RStudio Team, 2016). To test for differences and determine significance, we opted to use permutation tests, because they're more powerful than normal t-tests and more appropriate to analyse with small samples, since these tests work by resampling the observed data many times to determine the p-value (Ludbrook & Dudley, 1998; Mangiafico, 2016).

We chose to obtain result's significance using the "lmp" function of the "LmPerm" R package (Bolker, 2019; Wheeler, 2016). The upside of this function is that modest outliers have little effect on either normal distribution or permutations, but larger outliers affect permutation calculations less than normal theory calculations (Wheeler, 2016).

In the analyses concerning the distribution of wind direction and flight direction, we used the R package "circular" (Lund & Agostinelli, 2017) that performs circular statistics. This package allowed for the computation of plots for each construction period, as well as mean directions and tests of homogeneity between construction periods using Watson's two-sample homogeneity test (Lund & Agostinelli, 2017). Relatively to wind speed analyses, we compared construction periods in boxplots and determined significance using permutation tests.

2.4. Results

We selected a total of 257 movements to assess if there were changes in the flight behaviour of the studied species between the wind farm pre- and post-construction periods (Table 2 in Appendixes). The segmentation of movements according to the six height classes used produced a total of 346 segments considering the 1km buffer around the wind farm and 361 segments were obtained when considering the 1.5km buffer (Tables 5 and 6 in Appendixes). In both cases, a larger number of segments was obtained for the Griffon Vulture, whereas Egyptian Vulture and Black Stork showed the smallest number of segments.

Regarding flocking behaviour, the number of movements of Griffon Vultures flocks surpassed largely the number of individual records, *i.e.* 49 compared to 11 movements (Tab. 7 in Appendixes). Contrarily, in the Booted Eagle and, most remarkably, in the Honey Buzzard, individual movements outnumbered flock movements, *i.e.* 32 to 28 and 45 to 15, respectively.

2.4.1. Wind speed and direction

To evaluate the potential impact of wind speed and direction on the birds' flight behaviour we compared these parameters in the two time periods.

For the effect of wind speed on the birds' flight behaviour, we compared wind speed (m/s) between the pre- and post-construction periods for the whole set of movements of the five species (Fig. 6). We found that both periods had similar wind speed conditions (mean ± SD: Pre = 6.02 ± 2.04 m/s; Post = 5.57 ± 2.23 m/s; F = 2.72; $P = 0.10$), with both means falling in class 4 of the Beaufort scale. In fact, most wind measurements associated to the analysed movements vary between the Beaufort classes 3 (Pre = 43%; Post = 45%) and 4 (Pre = 39%; Post = 30%). Together, these two classes summarize 82% of wind speed in pre-construction and 75% in post-construction.

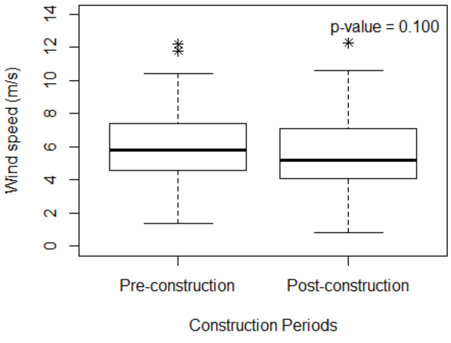

Figure 6: Differences in wind speed (m/s) between construction periods for the whole set of movements of the five species. Number of movements (n: Pre = 107; Post = 150).

To confirm if this pattern was observed for all species, we conducted the same comparison for each one (Fig. 7). The wind conditions associated to most species movements showed no differences between construction periods, with the mean of each period falling in Beaufort class 4 for the Booted Eagle (Pre = 6.64 ± 2.65; Post = 5.69 ± 1.70; F = 2.77; P = 0.10), Griffon Vulture (Pre = 5.68 ± 1.52; Post = 6.34 ± 2.24; F = 1.76; *P* = 0.19), Honey Buzzard (Pre = 5.72 ± 1.77; Post = 5.65 ± 2.30; F = 0.02; *P* = 0.90) and Egyptian Vulture (Pre = 5.46 ± 1.38; Post = 5.68 ± 2.18; F = 0.07; *P* = 0.79). Only in the case of Black Stork there was a significant difference with a lower wind speed measured during the post-construction phase (Pre = 6.58 ± 2.28; Post = 4.51 ± 2.39; F = 5.31; *P* = 0.03). In this case the wind speed means associated to pre- and post-construction movements fell respectively in Beaufort classes 4 and 3.

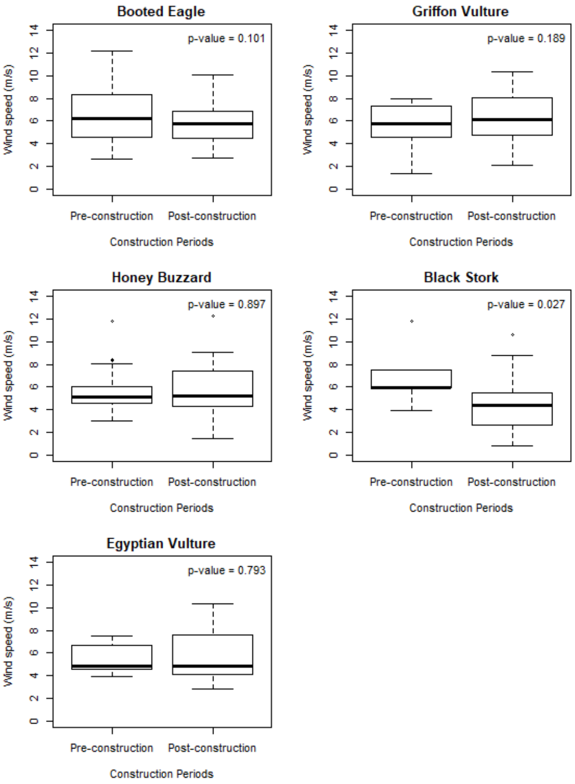

Figure 7: Differences in wind speed (m/s) between construction periods for movements of Booted Eagle, Griffon Vulture, Honey Buzzard (n Pre = 30; n Post = 30, for these three species), Black Stork (n Pre = 9; n Post = 30) and Egyptian Vulture (n Pre = 8; n Post = 30).

With respect to wind direction the measured values were more concentrated in the northwest and southeast origins during both construction periods (Fig. 8). However, Watson's two-sample test of homogeneity revealed that wind directions differed significantly between construction periods ($U^2 = 0.28$; $P < 0.01$). Besides, angular means were directed towards south-southwest in pre-construction and towards west-northwest in post-construction, which supports the test results. Despite the notable differences in wind direction between construction periods, most wind measurements originated from directions between west and north (Pre: 52%; Post: 65%), and between east and south (Pre: 36%; Post: 30%) in both periods. So, these directions encompassed 88% of wind direction measurements during pre-construction and 95% during post-construction.

We also analysed wind direction measurements associated to the movements selected for each species and compared between construction periods (Fig. 26, Annex). In terms of distribution, the species generally follow the same pattern as the one depicted in the diagrams for the whole data set (Fig. 8), with a tendency towards north to west, and east to south, despite some differences between species.

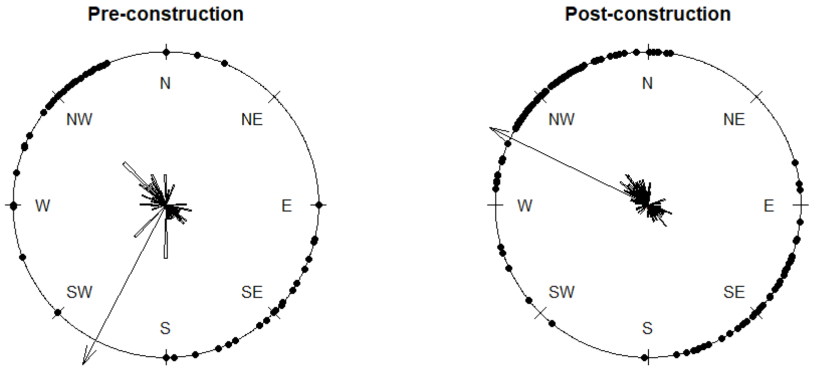

Figure 8: Distribution diagrams of wind directions and average wind direction (arrows) during pre-construction (left) and post-construction (right), using the whole set of selected movements of the five species (n Pre = 107; n Post = 150). Bar variation in the centre corresponds to a rose diagram of the frequency square root of each sector of wind direction. Arrows length represents the angular deviation: arrows near to the centre represent values close to 0 while arrows surpassing the circle represent values over 1.

According to the results of the Watson's test, Griffon Vulture ($U^2 = 0.17$; $0.05 < P < 0.10$), Black Stork ($U^2 = 0.10$; $P > 0.10$) and Egyptian Vulture ($U^2 = 0.07$; $P > 0.10$) do not have differences between construction periods, while Booted Eagle ($U^2 = 0.26$; $0.01 < P < 0.05$) and Honey Buzzard ($U^2 = 0.25$; $0.01 < P < 0.05$) have significative differences, which is supported by the means, since in pre-construction the mean for Booted Eagle is directed close to south-east and in post-construction is near west, while for the Honey Buzzard it is directed close to north-east in pre-construction and near west in post-construction. These differences may also be explained by distribution, since the wind roses within pre-construction of either species have values with a strong tendency towards south-west for Booted Eagle and towards south for the Honey Buzzards, but these tendencies are not visible in post-construction.

2.4.2. Flight direction

Although the mean directions of movements during the pre-construction and post-construction phases were directed respectively towards south-southwest and east (Fig. 9), they did not differ significantly (Watson's two-sample test of homogeneity; U2

= 0. 16; 0.05 < P < 0.10). In fact, flight directions were mostly towards the quadrant between south and west (Pre = 48%; Post = 43%) and between north and east (Pre = 37%; Post = 46%) for both construction periods. Therefore, these two quadrants involved 85% of the total flight directions in pre-construction and 89% in post-construction, which means that these are the main directions of movements that enter and exit the region of Sagres.

Comparisons between construction periods for each species were also made (Fig. 27, Annex). Considering data distribution, we can see that species generally follow the same pattern of flight direction as the one shown in the diagrams for the whole data set (Fig. 9).

We did not find differences for most species. The only exception was the Griffon Vulture (U2 = 0.29; P < 0.01), but the average flight direction only slightly changed from south east to east. This change may result from the differences in distribution tendency, since the wind roses show that values directed towards south-west are reduced in post-construction, while values towards north-east increased.

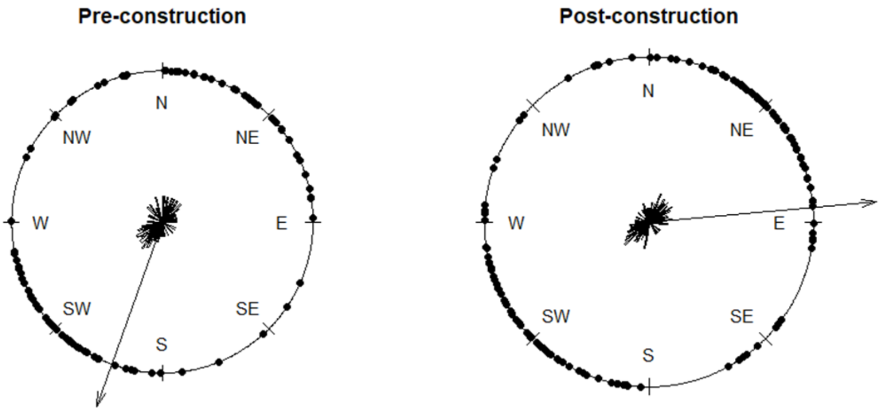

Figure 9: Diagrams with distribution of flight direction in degrees and mean of directions (arrows) for pre-construction (left) and post-construction (right), using the whole set of movements of the five species (n Pre = 107; n Post = 150). Bar variation in the centre corresponds to a rose diagram of the frequency square root of each sector of wind direction. Arrows length represents the angular deviation: arrows near to the centre represent values close to 0 while arrows surpassing the circle represent values over 1.

The following analyses intend to determine if birds displayed other types of meso-avoidance behaviours. During these analyses we found that a lot of results had the same values for both buffers, therefore we will refer bellow in which cases did this occur. Also, we will only present the plots for the 1km buffer as a representation of both if the results are the same and we'll present a plot for each buffer if the results differ between them.

2.4.3. Flying distance to wind turbines

Overall the distance at which the birds flew from the turbines did not change between the pre- and post-construction periods when considering the pooled movement data of the five migratory soaring bird species (Pre = 239.22 ± 185.59; Post = 240.19 ± 174.60; F = 0.01; *p* = 0.92; Fig. 10). In these analyses we found no differences between average distances obtained at the two buffers defined around the BSJWF area and therefore results presented here represent both buffers (Fig. 10). We observed this pattern for most of the analysed species; four of the five soaring bird species flew at comparable distances from the location of the turbines in both time periods, pre and post construction (Fig. 28, Annex. The only species with a contrasting behaviour was the Egyptian Vulture, whose individuals flew closer to the turbines' locations after their installation (Pre = 320.02m ± 205.55; Post = 258.98m ± 163.77; F= 3.92; df = 188; *p* = 0.049).

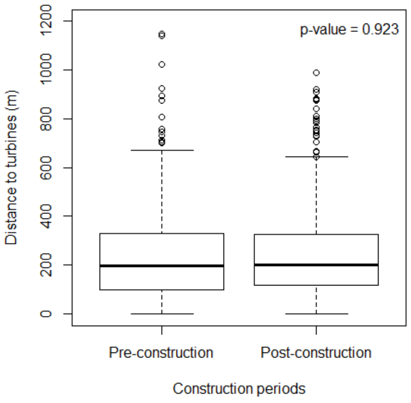

Figure 10: Differences in distance to turbines (m) between movements recorded during the two construction periods, using the whole set of five species (n Pre = 107; n Post = 150).

We also compared differences between species within each time period, but only for Griffon Vulture, Booted Eagle and Honey Buzzard, due to data limitations concerning the pre-construction period for the other two species (Fig. 11). In the pre-construction period there were no differences between species flying distance to turbine locations (Booted Eagle = 243.37m ± 212.66; Griffon Vulture = 207.06m ± 164.08; Honey Buzzard = 233.13m ± 174.72), whereas in the post-construction we found that these three species flew at different distances from the turbines, possibly due to an increase for the Booted and Honey Buzzard and a decrease for the Griffon Vulture (Botted Eagle = 248.48m ± 183.42; Griffon Vulture = 183.35m ± 135.13; Honey Buzzard = 243.76m ± 163.09).

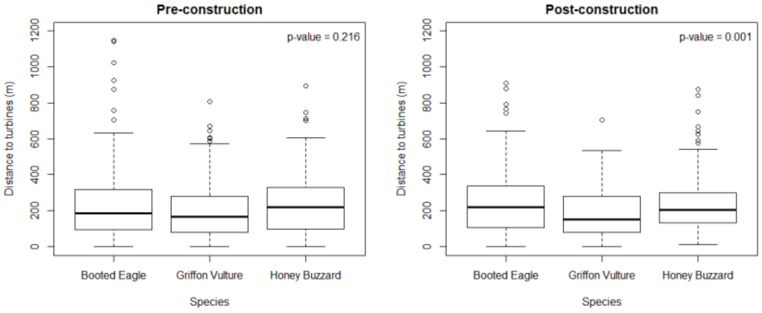

Figure 11: Differences in distance to turbines (m) between the movements of Booted Eagle, Griffon Vulture and Honey Buzzard for each construction period (n Pre = 30; n Post = 30 for these three species).

2.4.3.1. Distance to turbines among flocks

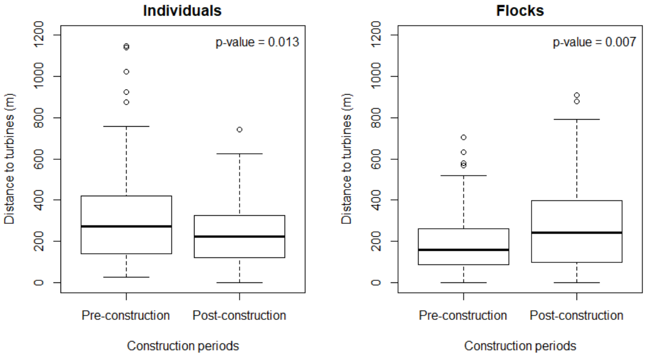

Figure 12: Differences in distance to turbines (m) between construction periods for movements of single individuals and flocks of Booted Eagle (n individual movements: Pre = 10; Post = 22; n flock movements: Pre = 20; Post = 8).

Booted Eagle individuals responded distinctively from flocks to the presence of the turbines (32 flock movements compared to 28 individual movements; Table 7, Annex): while isolated birds flew closer to the turbines after their installation, flocks increased the distance to turbines in the post-construction period (individuals: Pre = 320.42m ± 268.74 ; Post = 238.26m ± 152.00; F = 6.37; *p* = 0.01; flocks: Pre = 188.84m ± 147.95; Post = 277.80m ± 239.37; F = 7.61; p = 0.01; Fig. 12).

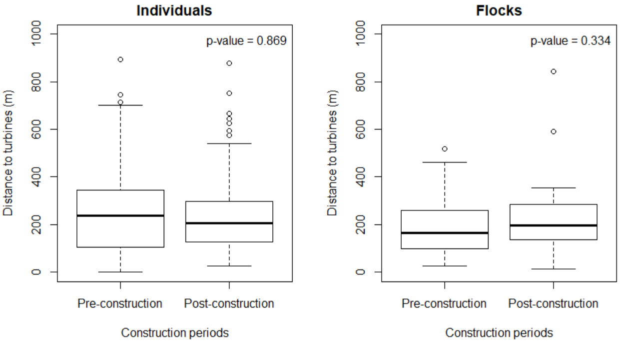

Figure 13: Differences in distance to turbines (m) between construction periods for movements of single individuals and flocks of Honey Buzzard (n individual movements: Pre = 21; Post = 24; n flock movements: Pre = 9; Post = 6).

In contrast, Honey Buzzards did not show any differences between individuals and flocks flying distance to turbines of among time periods (45 individual movements compared to 15 flock movements) (individuals: Pre = 250.18m ± 188.02; Post = 246.26m ± 164.41; F = 0.03; *p* = 0.87; flocks: Pre = 193.34m ± 132.32; Post = 226.90m ± 165.43; F = 0.95; *p* = 0.33; Fig. 13).

For the Griffon Vultures (Fig. 14) no differences were found in distance to turbines between periods for individuals and for the four flock size categories (individuals: Pre = 197.92m ± 131.43; Post = 217.21m ± 137.53; F = 0.21; $p = 0.65$), flocks with 2-20 individuals (Pre = 215.98m ± 161.81; Post = 206.92m ± 134.69; F = 0.07; $p = 0.79$), flocks of 21 to 100 (Pre = 235.82m ± 187.46; Post = 168.40m ± 172.44; F = 1.61; $p = 0.21$) and flocks of 201 to 1000 (Pre = 158.23m ± 108.87; Post = 173.99m ± 130.37; F = 0.28; $p = 0.60$). However, flocks with 101-200 individuals flew closer to turbines in the post-construction period (Pre = 281.48m ± 221.58; Post = 114.80m ± 69.87; F = 12.87; $p < 0.01$).

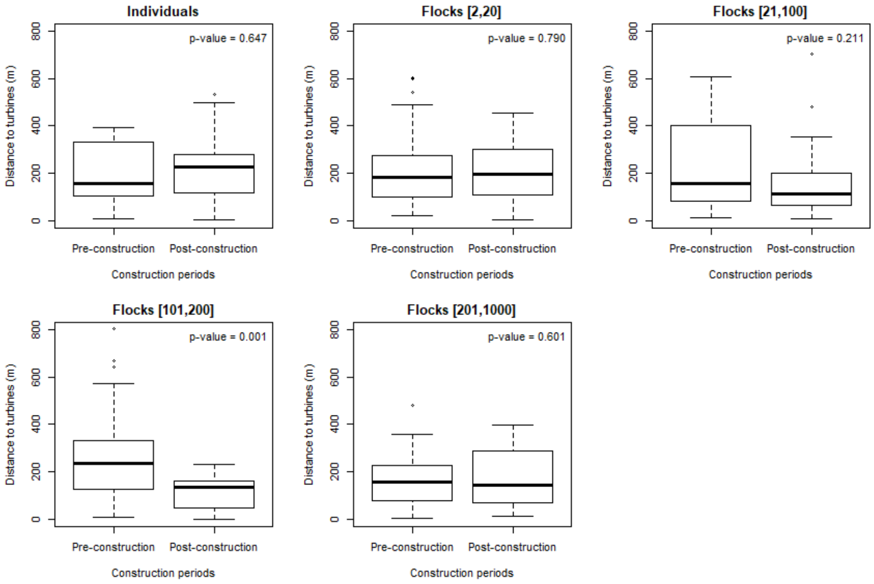

Figure 14: Differences in distance to turbines (m) between construction periods for movements of single individuals and flocks of Griffon Vulture (n individual movements: Pre = 3; Post = 8; n movements of flocks 2-20: Pre = 6; Post = 8; n movements of flocks 21-100: Pre = 7; Post = 4; n movements of flocks 101-200: Pre = 5; Post = 5; n movements of flocks 201-1000: Pre = 9; Post = 5).

2.4.4. Height classes

2.4.4.1. Distance to turbines among height classes

Due to the amount of data considered in the following analyses, the estimators and p-values that resulted from permutation tests are set in the Annex (Table 9).

When comparing distance to turbines between construction periods for movement segments within each height class we obtained significant differences in practically all height classes, with trajectories being at greater distances from turbines during post-construction (Fig. 29, Annex). The only exception was the analysis for the movements within a 1km buffer and in the 200-500m height class in which there was no differences between construction periods (Pre = 236.40m ± 181.77; Post = 269.09m ± 232.79).

To confirm the previous results, we also conducted the same analyse for each species independently (Figs. 15 - 18).

Booted Eagles flew at greater distances from the turbines during post-construction at all collision risk height classes (20-60m, 60-100m, 100-200m) (Fig. 15). However, no differences were found for both the <20m and 200-500m height classes, which may be related to the low numbers of segments for the <20m height class and the differences in number between construction periods for the 200-500m height class. We did not perform the comparison for the >500m height class due to lack of pre-construction observations (Tables 4 and 5, Annex). Buffers had the same significance for most height classes, except the 60-100m.

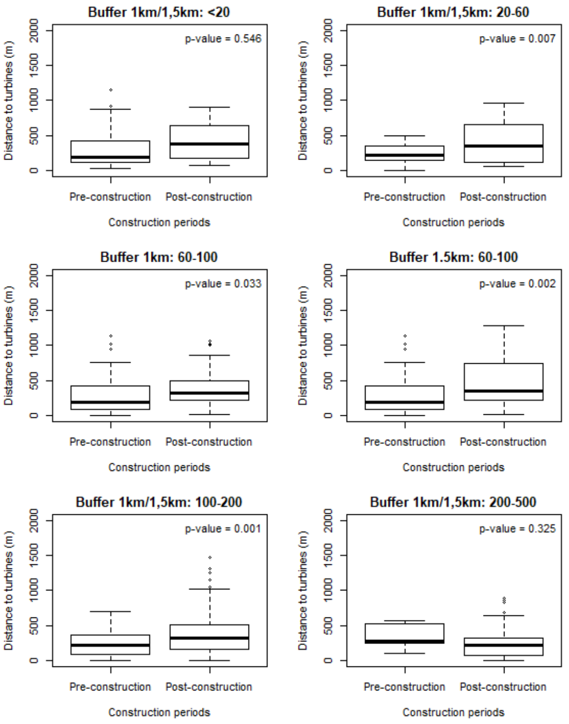

Figure 15: Differences in distance to turbines (m) between construction periods for movements of Booted Eagle in each height class for both buffers (1km and 1,5km). Number of segments (n) are represented in Table 5 and 6 in Appendixes.

Honey Buzzards also increased the distance to turbines during the post-construction period when flying between 20-60m and 100-200m height classes (Fig. 16). No significant differences were obtained for the remaining classes. Flight data from the lowest and the highest classes were scarce, in the <20 and >500m height class, although we performed the permutation tests, but the sample sizes were very small and these results need to be assessed with caution.

Griffon Vultures also flew at greater distances from the turbines during post-construction in almost all height classes (Figs. 17 and 18). The only exception were the movements at the 60-100m class within the 1km buffer that showed no significant difference between periods, although distances also tended to increase after the wind farm construction (1,5km buffer: Pre = 331.44m ± 196.43; Post = 601.62m ± 470.49), which may be related to the number of segments, because for post-construction the number greater in the 1,5km buffer than in the 1km buffer (Tables 4 and 5, Annex). In the >500m height class, buffers had the same significance. In the <20m and 20-60 height classes, the numbers of segments are very low, so the results are not representative.

While comparing differences between species in the use of each height class during the pre-construction periods we found no differences in the distance to the proposed locations of turbines for any class (Fig. 30, Annex). The difference was marginally significant in the 200-500m height class with Booted Eagles' movements showing higher mean distance than the other two species (Booted Eagle = 336.13m ± 161.28, Griffon Vulture = 209.32m ± 169.75, Honey Buzzard =

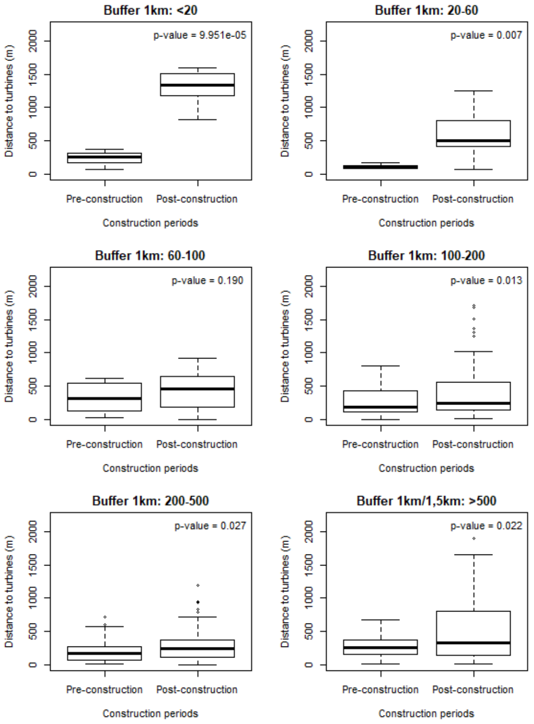

Figure 16: Differences in distance to turbines (m) between construction periods for movements of Honey Buzzard in each height class for both buffers (1km and 1,5km). Number of segments (n) are represented in Table 5 and 6 in Appendixes.

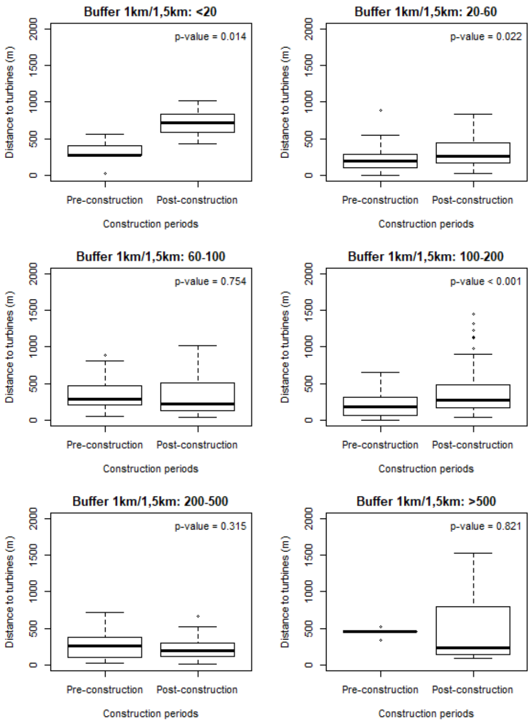

Figure 17: Differences in distance to turbines (m) between construction periods for movements of Griffon Vulture in each height class for the 1km buffer. Number of segments (n) are represented in Table 5 and 6 in Appendixes.

267.77m ± 210.65). Booted Eagle doesn't have values in the >500m height class and despite the differences between Griffon Vulture and Honey Buzzard (Griffon Vulture = 276.99m ± 182.32, Honey Buzzard = 445.74m ± 65.55), there is a great difference in the number of segments between them, so the test significance may not represent the data.

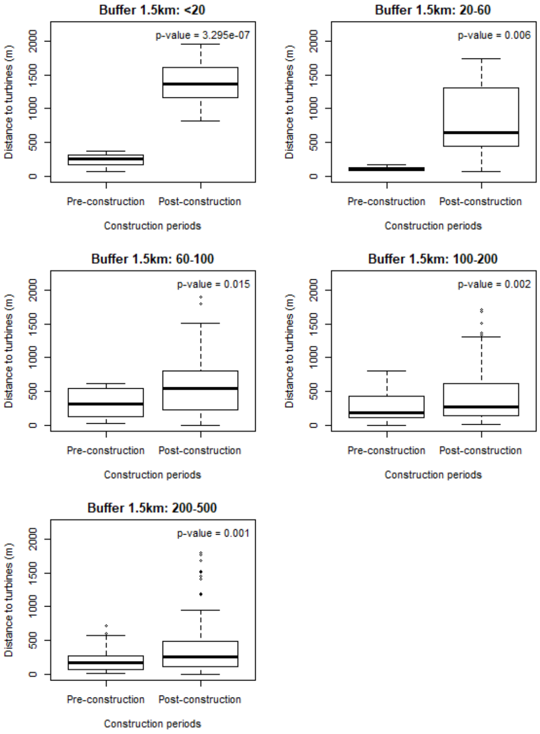

Figure 18: Differences in distance to turbines (m) between construction periods for movements of Griffon Vulture in each height class for the 1,5km buffer. Number of segments (n) are represented in Table 5 and 6 in Appendixes.

During the post-construction period species differed significantly in the distance to turbines when using the < 20m (Booted Eagle: 1km/1,5km = 432.60m ± 300.28; Griffon Vulture: 1km = 1286.90m ± 306.58; 1,5 km = 1395.68m ± 318.40; Honey Buzzard: 1km/1,5km = 720.45m ± 222.16) and 20-60m (Booted Eagle: 1km/1,5km = 419.24m ± 307.52; Griffon Vulture: 1km = 605.99m ± 353.17; 1,5 km = 838.10m ± 518.80; Honey Buzzard: 1km/1,5km = 319.71m ± 202.72), with Griffon Vultures flying at greater distances (Fig. 31, Annex). In the classes 60-100m and 200-500m, but only when considering movements within the 1,5km buffer, distances also differed and again Griffon Vultures flew at greater distances, followed by Booted Eagles and with Honey Buzzards flying closer to the turbines (60-100m: Booted Eagle = 479.35m ± 329.57, Griffon Vulture = 601.62m ± 470.49, Honey Buzzard = 327.72m ± 262.14; 200-500m: Booted Eagle = 260.14m ± 232.72, Griffon Vulture = 409.61m ± 449.84, Honey Buzzard = 218.95m ± 145.09). For the other height classes, 100-200m and >500m, no differences were found.

2.4.4.2. *Flight vertical profile*

We assessed if the species flight vertical profile changed between the two time periods, before and after the installation of the wind turbines, by analysing the relative difference of movements in each height class. Our data shows that the three species decreased the use of the lower height class in post-construction (<20m), although by a small amount for Honey Buzzard. The 20-60m class was less used by Booted Eagles and Honey Buzzards during post-construction, whereas Griffon Vulture increased the use of this class. For the 60-100m class, the three species had contrasting results, Booted Eagle decreased the use in post-construction, while Griffon Vulture increased and Honey Buzzard showed practically no difference (-0.75% variation). Both Booted Eagles and Griffon Vultures used slightly less the 100-200m class during post-construction (-16,7% and -10,1% variation, respectively), while Honey Buzzard remained unchanged (2,6% variation). All species increased the use of the 200-500m class during post-construction. Finally, the >500m class was less used by Griffon Vultures and more used by Honey Buzzards during post-construction. The selected movements of Booted Eagles in this class were only registered during the post-construction stage, therefore we could not estimate the change in the proportion (Table 8, Annex; Fig. 19, left).

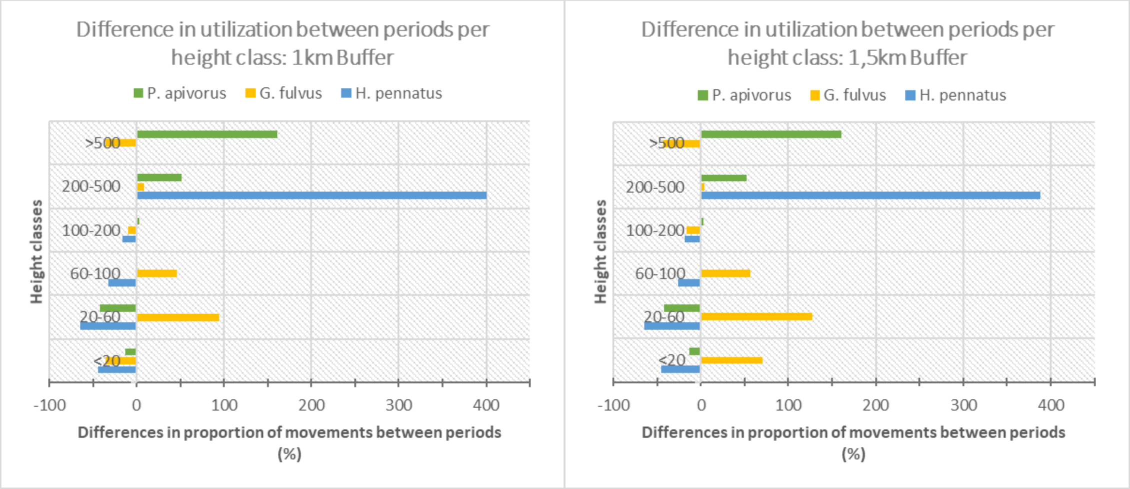

Figure 19: Graphic representation of the differences in proportion of movements for each height class and within each buffer (1km and 1,5km), for the Booted Eagle (blue), Honey Buzzard (green) and Griffon Vulture (yellow) between pre- and post-construction phases. Represented values are the same as in Table 7, Annex. Number of movements (n) are in Tables 4 and 5, Annex.

The analyses on the variation in the use of the different height classes between construction phases using the movements within the wider, 1,5km buffer (Table 8, Annex; Fig. 19, right), were very similar to those mentioned above. The only clear difference emerged relatively to the use of the <20m height class by Griffons Vultures, which showed an increase in the post-construction phase, contrarily to what we obtained when using the 1km buffer data.

We performed the flight vertical profile analysis for the Black Stork and Egyptian Vulture considering the flight height data recoded into two categories, high risk and low risk categories because of the lack of data for most height categories for one of the time periods (Table 8, Annex).

In the 1km buffer, Black Stork decreases de use of high-risk classes and increases slightly the use of low-risk classes in post-construction. Conversely, Egyptian Vulture increases the use of high-risk classes and decreases the use of low-risk classes. The results using the movements within the 1.5km buffer were very similar, but showed a larger increase in the use of classes without risk by Black Storks (Table 8, Annex; Fig. 20).

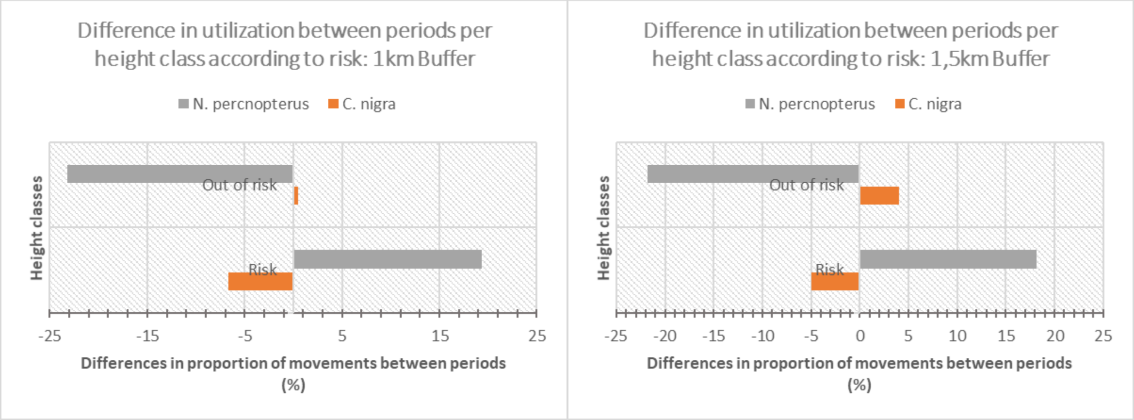

Figure 20: Graphic representation of the differences in proportion of movements for each height class and within each buffer (1km and 1,5km), for the Black Stork (orange) and Egyptian Vulture (grey). between pre- and post-construction phases. Represented values are the same as in Table 7, Annex. Number of movements (n) are in Tables 4 and 5, Annex.

2.4.5. Movement linearity

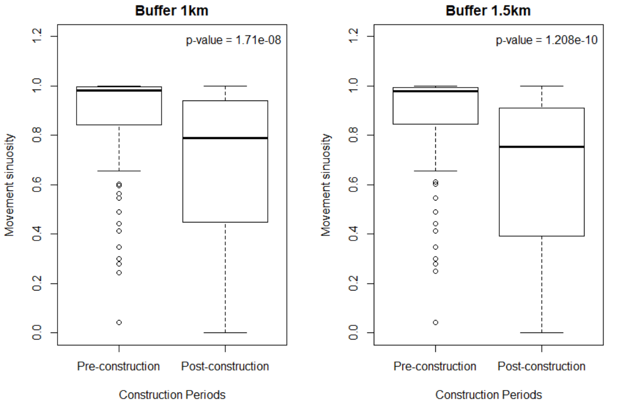

Figure 21: Differences in linearity between construction periods for both buffers (1km and 1,5km), using the whole set of movements of five species (n Pre = 107; n Post = 150).

The following analyses also have substantial amounts of data, so the estimators and p-values that resulted from permutation tests are set in the Annex (Table 10).

By comparing bird movement linearity when traversing the wind farm between construction periods for all 5 species (Fig. 21), we found that the movements are more linear in pre-construction (1km/1,5km = 0.88 ± 0.20), *i.e.* a value of 1 corresponds to a perfectly straight movement, than in post-construction (1km = 0.68 ± 0.31; 1,5km = 0.65 ± 0.31).

A detailed species analysis also revealed that most species have movements with lower values of linearity in post-construction, *i.e.* more sinuous movements (Fig. 32, Annex). The only exception is the Egyptian Vulture, as the flight linearity of this species had similar estimated values between construction periods (Pre: 1km/1,5km = 0.83 ± 0.21; Post: 1km = 0.67 ± 0.31, 1,5km = 0.66 ± 0.30).

Finally, we compared differences in movement linearity between three most represented species (Booted Eagle, Griffon Vulture and Honey Buzzard) for each construction period (Fig. 22). During pre-construction no differences were found between species (Booted Eagle: 1km/1,5km = 0.92 ± 0.12; Griffon Vulture: 1km = 0.83 ± 0.27, 1,5km = 0.84 ± 0.27; Honey Buzzard: 1km/1,5km = 0.87 ± 0.20). For the post-construction period there was a marginal difference in flight linearity among species, with Griffon Vultures showing the most sinuous movements (Booted Eagle: 1km = 0.76 ± 0.31, 1,5km = 0.72 ± 0.30; Griffon Vulture: 1km = 0.56 ± 0.33, 1,5km = 0.53 ± 0.31; Honey Buzzard: 1km = 0.65 ± 0.33, 1,5km = 0.64 ± 0.33).

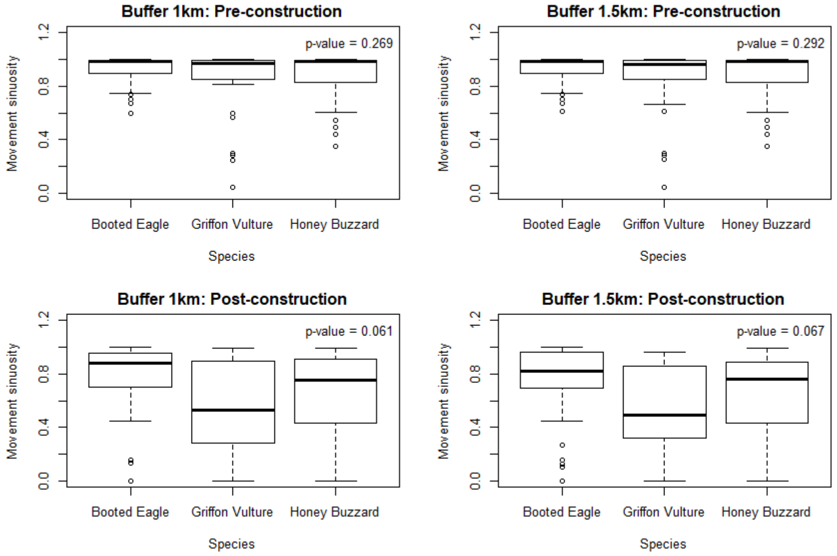

Figure 22: Differences in linearity between the movements of Booted Eagles, Griffon Vultures and Honey Buzzards within both buffers (1km and 1,5km) and for each construction period (n Pre = 30; n Post = 30 for these three species).

2.4.5.1. Movement linearity and flocking behaviour

By comparing movement linearity of each flocking class within each species, we found that while Booted Eagles flying individually did not change their flight pattern (Fig. 23) flocks altered their movements, making less linear trajectories during post-construction (Pre: 1km/1,5km = 0.98 ± 0.02; Post: 1km = 0.71 ± 0.44; 1,5km = 0.74 ± 0.39).

In contrast, both the individual and flocks of Honey Buzzard adopted less linear routes after the construction of the wind farm (Pre: 1km/1,5km = 0.83 ± 0.22; Post: 1km = 0.64 ± 0.32; 1,5km = 0.63 ± 0.32; Fig. 24).

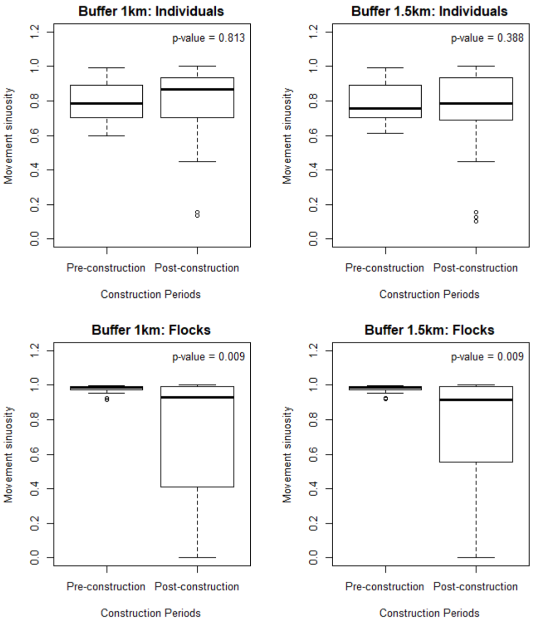

Figure 23: Differences in linearity between construction periods for movements of single individuals and flocks of Booted Eagle (n individual movements: Pre = 10; Post = 22; n flock movements: Pre = 20; Post = 8), within both buffers (1km and 1,5km).

Griffon Vultures had a similar pattern to that observed for the Booted Eagle. Individual Griffon Vultures had similar values of route linearity between the pre- and post-construction phases (Fig. 25), but flocks of Griffon Vultures performed more sinuous movements in the post-construction phase. The only exception were flocks composed of 21 to 100 birds, which had similar linearity values in the pre-construction and post-construction.

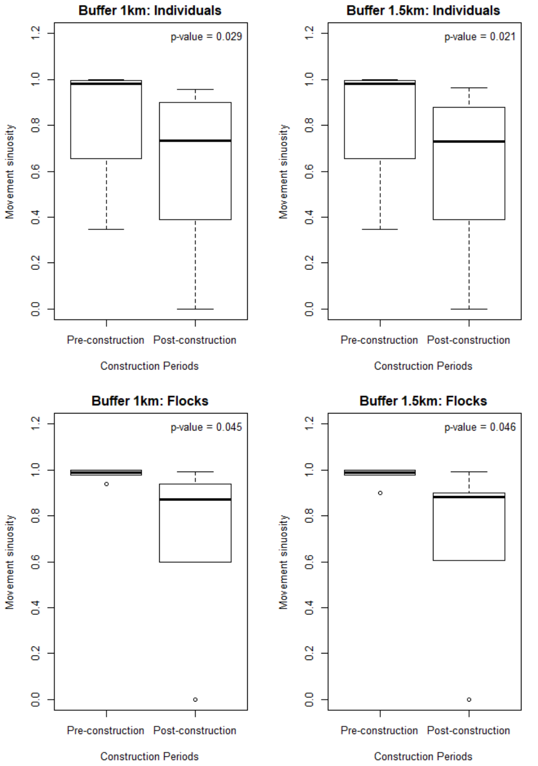

Figure 24: Differences in linearity between construction periods for movements of single individuals and flocks of Honey Buzzard (n individual movements: Pre = 21; Post = 24; n flock movements: Pre = 9; Post = 6), in both buffers (1km and 1,5km).

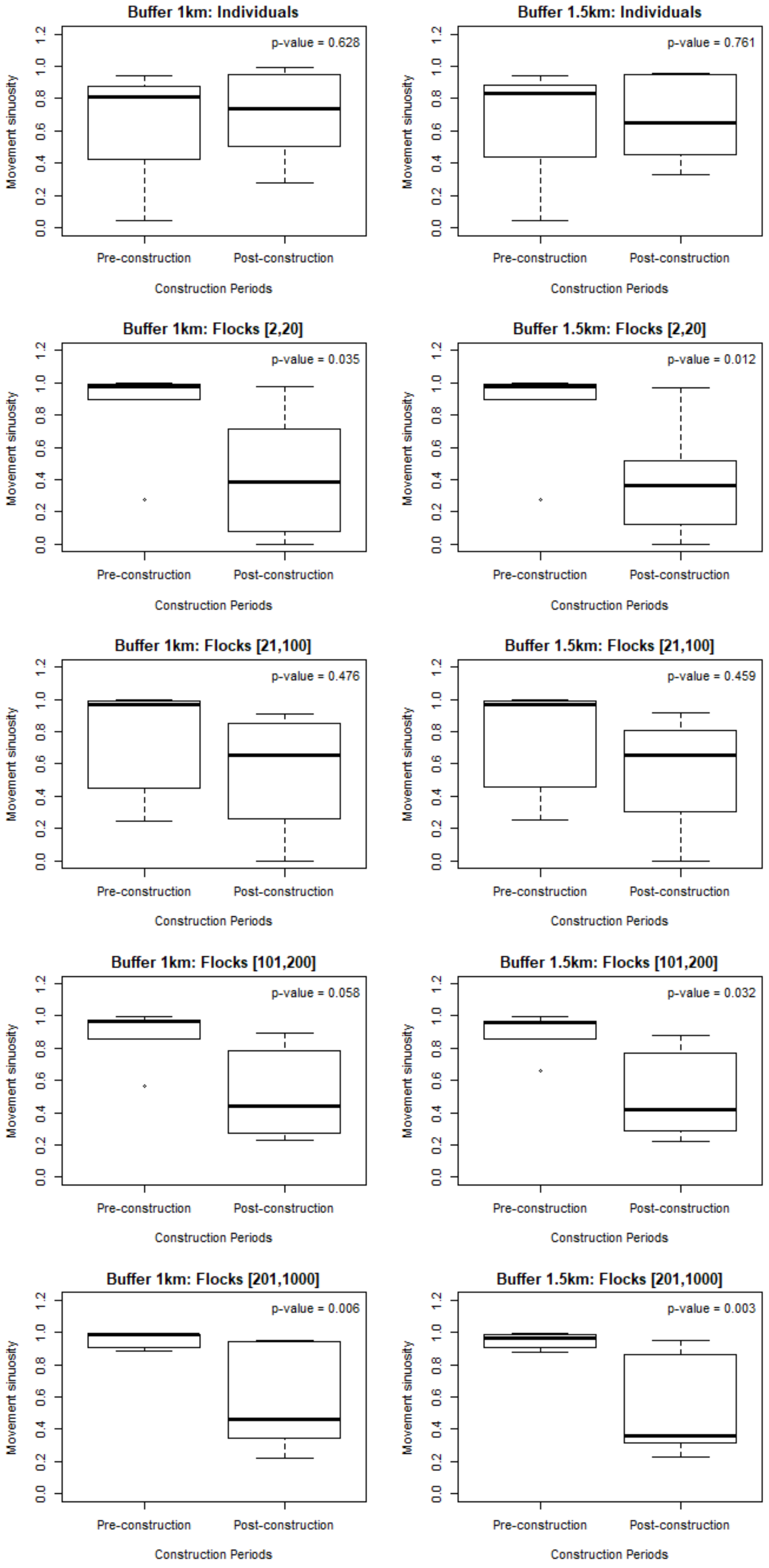

Figure 25: Differences in linearity between construction periods for movements of single individuals and flocks of Griffon Vulture (n individual movements: Pre = 3; Post = 8; n movements of flocks 2-20: Pre = 6; Post = 8; n movements of flocks 21-100: Pre = 7; Post = 4; n movements of flocks 101-200: Pre = 5; Post = 5; n movements of flocks 201-1000: Pre = 9; Post = 5), in both buffers (1km and 1,5km).

2.5. Discussion

When faced with an obstacle, birds may react by adopting avoidance responses. These reactions may contemplate avoidance of the whole wind farm, *i.e.* macro-avoidance, avoiding individual turbines or flying between rows, *i.e.* meso-avoidance and last-second avoidance, *i.e.* micro-avoidance (Cook *et al.*, 2014; May *et al.*, 2015). Different species may perform different avoidance behaviours, as some may react by increasing flight altitude, *i.e.* vertical avoidance, or others may be more prone to changing their flight trajectory, *i.e.* horizontal avoidance (Cook *et al.*, 2014; Johnston *et al.*, 2014; Plonczkier & Simms, 2012). Therefore, the type of response will vary with species-specific characteristics, such as manoeuvrability and agility, which depend on a bird's WL and AR (Agostini *et al.*, 2015; de Lucas *et al.*, 2008; Janss, 2000; Newton, 2008; Rayner, 1988). Birds of a same species may also have different avoidance responses depending on flocking behaviour (Croft *et al.*, 2015; Desholm & Kahlert, 2005; Garvin *et al.*, 2011).

Although other multi-species studies have been conducted on raptors (Barrios & Rodríguez, 2004; Cabrera-Cruz & Villegas-Patraca, 2016; Pearce-Higgins *et al.*, 2012; Péron *et al.*, 2017; Villegas-Patraca *et al.*, 2014) and seabirds (Johnston *et al.*, 2014; Krijgsveld, 2014), there is still a lack of information on the occurrence and inter-specific variation of vertical and horizontal avoidance behaviour by birds, especially for threatened species (Barrios & Rodríguez, 2004; Carrete *et al.*, 2009). In our study we found evidence that most analysed soaring bird species adopt avoidance behaviours toward wind turbines, which supports information on these topics. Moreover, we also confirmed that avoidance behaviour can be species specific because the two species of vultures showed less notable avoidance reactions when compared to the remaining species. We also identified that birds of the same species may show intra-specific avoidance variation depending on if they are flying alone or in flocks.

2.5.1. Wind effect

Wind conditions, namely wind direction and speed, are some of the main factors that affect flight behaviour and, consequently, collision risk. Although birds are more active at low wind speeds (Barrios & Rodríguez, 2004; May *et al.*, 2015), some fly in strong winds and that may pose difficulties to soaring birds as they reduce the availability and creation of thermals, leading birds to rely upon orographic lift (Johnston *et al.*, 2014). The type of terrains generally associated with orographic lift are also areas of interest for the implementation of wind farms (Barrios & Rodríguez, 2004; Johnston *et al.*, 2014; Pearce-Higgins *et al.*, 2009), because these are zones of collision risk for birds since bird routes may intersect with turbines. In the case of the BSJWF this would probably imply an increase in the number of bird routes along that would intersect turbines due to their locations on the top of ridges of a valley and, consequently, a greater risk of collision. Moreover, flying against strong headwinds or tailwinds may increase collision risk, because birds tend to fly lower, which places them at the wind turbines level (Johnston *et al.*, 2014; R. T. Watson *et al.*, 2018). Headwinds may be particularly troublesome, since the birds' flight speed is reduced, making them more vulnerable to turbine blades rotating at high speeds (Jenkins *et al.*, 2018). However, very low wind speeds may also increase collision risk, due to weak formation of thermals and resulting poor lifts for birds (Barrios & Rodríguez, 2004; R. T. Watson *et al.*, 2018).

In the data set of soaring bird movements we analysed wind speed and it did not vary significantly between construction periods for most species. In fact, three quarters or more of the analysed movements in each period were registered under gentle to moderate winds (classes 3 and 4 in the Beaufort scale; Quaschning, 2005) which makes the pre-construction and post-construction periods comparable. Even in the single case (Black Stork) where a significant decrease in wind speed was found between movements in the pre- and post-construction phases, this variation occurred only in the two Beaufort classes 3 and 4. These results confirm findings of other studies where birds are more active at low wind speeds (Barrios & Rodríguez, 2004; May *et al.*, 2015).

Regarding wind direction, there were differences between construction periods for the whole data set, albeit the two main origin quadrants remained the same (east-south and especially north-west). The species analyses revealed that only for the flights of the Booted Eagle and Honey Buzzard wind direction conditions differed between the construction periods. Yet, even in these cases most of the movements were performed under similar wind direction conditions (Fig. 26, Annex). Nearly all movements analysed were along an axis approximately northeast–southwest, corresponding to a route entering or leaving the southwest corner of Portugal, which constitutes a dead-end for the migration of soaring birds. This was also the case for the Griffon Vulture and the difference obtained in flight direction was merely due a higher proportion of entry movements (directed towards southwest) in the pre-construction than in the post-construction sample.

Apart from the relatively low intensity of wind during the studied movements, the dominant wind were mostly lateral to the prevailing route of migratory soaring birds in the BSJWF, which means the birds did not face the impact of headwinds and tailwinds that, as mentioned before, represent greater risk (Jenkins *et al.*, 2018; Johnston *et al.*, 2014; R. T. Watson *et al.*, 2018). Therefore, neither the variation in wind speed or direction between the two construction periods were likely to have an effect on the manoeuvrability of birds.

2.5.2. Avoidance behaviour and inter-specific variation

2.5.2.1. Horizontal avoidance

Flight distance to turbines locations did not change after the installation of the wind farm (post-construction period) for the overall set of soaring bird movements or among each species. The only exception to this apparent lack of meso-avoidance response was the Egyptian Vulture: in this case individuals flew closer to turbines in the post-construction period. Also, and despite the lack of differences in the distance to turbines locations between species during the pre-construction period, we found a difference during the post-construction, probably because there was a trend for a decrease in the distance to turbines by Griffon Vultures in this period (Fig 9; Fig 26, Annex). This trend was significant for medium-sized flocks of Griffon Vultures (between 101 and 200 individuals), although this result must be interpreted cautiously due to the small sample sizes. Additionally, our data also indicate that Booted Eagles flying alone during the post-construction period flew closer to turbines than when flying in flocks.

One possible explication for this behaviour, in cases where temporary shutdown of turbines was applied, is that birds may fly closer to idle wind towers compared to when they are rotating, as other studies have reported(de Lucas *et al.*, 2004; Smallwood *et al.*, 2009; Krijgsveld, 2014). This behaviour may depend on species and site factors, as

Larsen & Guillemette (2007) found no differences in behaviour relative to the operational state of turbines.

It may also be related to an attraction to the wind farm. Attraction has been described by other studies as inversely related to distance to the wind farm or an increase in numbers of birds within a wind farm (Cook *et al.*, 2014; Skov *et al.*, 2016). This behaviour may occur associated with adverse weather conditions (*e.g.* headwinds), an increase in food availability or existence of perching structures (Cook *et al.*, 2014; Desholm & Kahlert, 2005; Krijgsveld, 2014; Skov *et al.*, 2016). However, none of these conditions are likely to be the case for neither vulture species at BSJWF, so other factors must be at play. Possibly, as most of the birds that migrate to Sagres are juveniles on their first migration (STRIX unpub. data) that get temporarily lost in a dead-end, they may be attracted to wind turbines due to curiosity, looking for reference marks in the landscape or potential perching places, and revealing unawareness of the risks that wind turbines may represent.

Birds that fly closer to turbines are exposed to greater collision risk than birds that display avoidance behaviour (Dahl *et al.*, 2013; Garvin *et al.*, 2011; Krijgsveld, 2014; May, 2015; Pearce-Higgins *et al.*, 2009). Hence this lack of avoidance behaviour – or even attraction to the turbines – may explain why Griffon Vultures are one of the species most affected by collisions with wind turbines (Barrios & Rodríguez, 2004; de Lucas *et al.*, 2012; Martínez-Abraín *et al.*, 2012) and why Egyptian Vulture is also affected by collisions (Carrete *et al.*, 2009).

In the case of Booted Eagle, individuals and flocks showed contrary results, but these support the findings of Garvin *et al.* (2011), where observations of raptors without response to wind turbines were generally individuals on a straight trajectory crossing the wind farm, and also findings of other studies that recorded flocks displaying avoidance behaviour when confronted with wind farms (Cabrera-Cruz & Villegas-Patraca, 2016; Desholm & Kahlert, 2005; Plonczkier & Simms, 2012). Also, individuals reduce flight distance to wind turbines, which may be a sign of attraction (Skov et al., 2016). This species hunts during migration and possible prey availability in BSJWF area may attract these birds closer to turbines (Cook et al., 2014; Desholm & Kahlert, 2005; Krijgsveld, 2014), which may increase risk of collision, especially due to distraction while hunting (Marques et al., 2014; J. W. Watson et al., 2018). In general analyses of flight distance to turbines, we did not find differences for the whole set of movements of each species, but these results show that other factors like flocking influence the avoidance behaviour and that flight distance analyses must be complimented with other variables.

Small flocks of birds have greater ability to avoid singles obstacles and are more likely to cross arrays, *i.e.* behave similarly to individual birds (Cook *et al.*, 2014). In our selected movements, Honey Buzzards have relatively small flocks (max. number of birds in a flock = 6), which may explain why flocks did not have differences in distance and seem to behave similarly to individuals.

We also found that most species performed more sinuous movements (*i.e.* less linear) during post-construction with the exception of the Egyptian Vulture, which also showed an increase in the sinuosity after the installation of wind turbines but it was non-significant. Despite this generalized response, Griffon Vultures had movements more sinuous in pre-construction than the Booted Eagle and Honey Buzzard. An increase in sinuosity may represent another type of avoidance response more similar to micro-avoidance than the variation in distance to turbines, without occurring last-second evasion.

Our results also revealed that species avoidance behaviour can change markedly according to the number of soaring birds flying together. The individuals of Booted Eagle have no differences in linearity between periods, which along with flying at closer distances to turbines after the construction may imply greater risk, while flocks flew at greater distances from turbines and made more sinuous movements in post-construction. This pattern of increased avoidance with increasing number of birds flying together has also been reported by Garvin *et al.* (2011), which observed the non-response (straight trajectory) of individual raptors near wind turbines whereas flocks displayed avoidance behaviour when confronted with wind farms (Cabrera-Cruz & Villegas-Patraca, 2016; Plonczkier & Simms, 2012).

On the other hand, both individuals and flocks of Honey Buzzards have movements more sinuous in post-construction, although no differences were found in terms of distance to turbines. Honey buzzards have the lowest wing loading of the group (*i.e.* highest manoeuvrability; Janss, 2000; Rayner, 1988), therefore better ability to avoid obstacles (Drewitt & Langston, 2006; Péron *et al.*, 2017; Pescador *et al.*, 2019), so these birds may be able to correct slightly their flight trajectory to avoid an obstacle instead of increasing distance to turbines and since flocks are relatively small, their reaction can be similar to individuals (Croft *et al.*, 2015).

2.5.2.2. Vertical avoidance

Our results showed that Black Storks, Booted Eagles and Honey Buzzards favour higher flights in post-construction when flying near or across the windfarm, probably showing signs of vertical avoidance like what has been reported in other studies (Johnston *et al.*, 2014; Krijgsveld, 2014). Moreover, Booted Eagles and Honey Buzzards also flew at greater distances from turbines when at risk height classes and reduced the use of these classes after BSJWF construction which may indicate that these species displayed both vertical and horizontal avoidance. These results do not necessarily contradict the general analyses of distance to turbines, but complements them because they show that, despite the lack of differences in distances for the whole movement, there is a clear effect of the height classes. While most avoidance analyses are performed for the horizontal or the vertical dimensions separately, soaring birds may combine both types of avoidance when flying across these areas. This is supported by reports of avoidance patterns observed in other migratory species, such as geese (Plonczkier & Simms 2012).

The notable avoidance responses of Booted Eagles and Honey Buzzards may be explained by species-specific traits, since these species have the lowest values of WL (*i.e.*, highest manoeuvrability; Janss, 2000; Rayner, 1988) and some of the highest values of AR (*i.e.*, greater ability to use powered flight; Agostini *et al.*, 2015). Therefore, they have better ability to climb thermals (Shamoun-Baranes *et al.*, 2009) and avoid obstacles (Drewitt & Langston, 2006; Péron *et al.*, 2017; Pescador *et al.*, 2019) than the remaining species.

Griffon Vultures, however, showed a markedly different response to the wind farm; they increase the use of high-risk height classes in post-construction and reduce or barely increase the use of classes above the wind turbines However, these vultures showed more sinuous movements after the implementation of the BSJWF and also tended to fly at greater distances from turbines in most height classes comparing to Booted Eagles and Honey Buzzards. These birds have the longest post-construction movements of the selected species, even after the buffers cut, and this may be influencing the results, since segments of height classes at greater distances from turbines will have greater minimal distances than the general analyses. Egyptian Vultures did not show hesitancy around wind turbines - no differences in linearity were found -, instead these smaller vultures even seem attracted to them as they reduced the flying distance to turbines and increased the use of height risk classes. This attraction to wind turbines can explain why these vultures suffer high mortality when flying near or crossing wind farms (Carrete *et al.*, 2009).

Marques *et al.* (2019) report that areas within ca. 674m around the turbines were less used than expected by Black Kites (*Milvus migrans*) given their uplift potential. The ridges where BSJWF is located also have a good uplift potential, thus it would be expected that birds made use of it and would reduce this use after the installation of turbines. However, most of our results of distance to turbines do not show differences between construction periods. In our study birds fly closer to turbines (less than 600m) than the distance reported by Marques *et al.* (2019). Therefore, other factors than uplift may be affecting the response of soaring species in our study.

2.5.3. Study gaps and constraints

Main constraints affecting wind farm monitoring data are often relative to differences between pre- and post-construction data since pre-construction monitoring may involve methodological differences or be less intensive than during post-construction (Carrete *et al.*, 2010; Janss *et al.*, 2010; Jenkins *et al.*, 2018; Scottish Natural Heritage, 2009; Villegas-Patraca *et al.*, 2014). However, we used distance buffers around the wind farm to cut all movements to compare bird movements only on area of the windfarm and its close proximity thereby, limiting the impact of the different area covered by observers in the two time periods. By selecting a similar number of bird movements for each time period we also attenuated any bias due to higher number of tracked movements in the post-construction period.

Another issue with potential impact in the results is data spatial accuracy and associated to observation error. Although the observers contracted by STRIX are experienced in monitoring at the BSJWF, sometimes it may be difficult to determine accurately the birds locations and flight altitude (Cleasby *et al.*, 2015; Cook *et al.*, 2014; Krijgsveld, 2014) and by communicating with observers at other vantage points and assessing the accurate location by triangulation of different azimuths. Relatively to height, observers used the previously known heights of existing trees, wind turbines and meteorological towers as references. The observation errors associated to the estimation of exact location and height most likely increased for birds that flew at a considerable distance from the BSJWF. However, because we selected only the movement stretches within the 1.5 km buffers from the windfarm the associated error probably had a low impact in our results.

Some of our results show reactions that may entail avoidance responses, however we did not find differences in distance to turbines between periods for most species in the general analyses. This is possibly a result of the restricted number of movements per species and period that we selected (*i.e.* max. number of 30), but we were conditioned by sample size of pre-construction data available since we aimed for a similar number of movements between construction periods and selecting over 30 movements per species and period could results in notable differences. We used two strategies to overcome this limitation. We pooled factor categories for height analysis of Egyptian Vultures and Black Storks, for which we only compared between height classes according to risk. In analyses of distance to turbines for each height class, some height classes were underrepresented due to data limitations, *i.e.* <20m and >500m, so the results for these two classes must be carefully considered.

In analyses comparing flocking behaviour, we faced marked differences between species in the sample size of movements available for individuals and flocks. For Honey Buzzard, movements of individuals were much more represented, so we grouped all remaining movements in a single flocking class. While for Griffon Vulture, we were able to reduce the effect of the greater number of flock movements by dividing them into several classes.

2.5.4. Conclusions

With this study we found inter-specific (*i.e.* among species) and intra-specific (*i.e.* between individuals and flocks of a same species) variation in avoidance behaviours. In general analyses, Griffon Vultures flew closer to turbines than the remaining species and Egyptian Vultures reduced the distance to the turbines' locations after their installation. Moreover, both increased the use of high-risk classes after the construction of turbines. Therefore, vultures seem to display attraction to wind turbines, which may explain the mortality due to collision found for these species(Barrios & Rodríguez, 2004; Carrete et al., 2009; de Lucas et al., 2012; Martínez-Abraín et al., 2012).

Individuals of Booted Eagle also displayed horizontal attraction to turbines, whereas flocks clearly avoid wind turbines. In the case of Honey Buzzards, both individuals and flocks behaved similarly, not showing meso-avoidance, but increasing movement sinuosity, which may be considered more akin to micro-avoidance. Additionally, Black Storks, Booted Eagles and Honey Buzzards displayed vertical avoidance, showed by an increasing in the use of lower risk height classes after the construction of the wind farm. Therefore, our results for Booted Eagle and Honey Buzzard show that raptors may combine both horizontal and vertical avoidance behaviours (Plonczkier & Simms 2012).

A better understanding of avoidance behaviour is important as both the occurrence or absence of these type of behaviours may have consequences to birds: species that do not avoid wind turbines are more prone to collisions (Dahl *et al.*, 2013; Krijgsveld, 2014; May, 2015), while birds that avoid the turbines or even the whole wind farm can suffer with displacement and consequent habitat loss (Garvin *et al.*, 2011; Kelsey *et al.*, 2018; Pearce-Higgins *et al.*, 2009), or barrier-effects and possible higher energy demands (Desholm & Kahlert, 2005; Masden *et al.*, 2009). Identifying which species show avoidance patterns is also important, as it may help to improve or understand the type of mitigation measures that may be efficient in each case. There is still a need of studies that analyse the effectiveness of mitigation measures (Marques *et al.*, 2014; Pescador *et al.*, 2019; Tomé *et al.*, 2017) and differences in birds' behaviour after the application of these measures.

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3. Final Considerations

Our study makes a multi-species comparison of avoidance behaviours, adding information about species-specific differences. Besides, we also show how two endangered species in the Iberian Peninsula (Egyptian Vulture and Black Stork; Cabral et al., 2005; ICNB, 2008) behave close to wind turbines. Although our analyses for both species are limited due to the shot amount of available data during the pre-construction phase, studies such as this are important to increase the knowledge about these species, since there is a lack of studies in Europe providing information about avoidance behaviour by endangered species towards wind turbines (Carrete *et al.*, 2009). Our analyses regarding the use of distinct height classes bring also additional useful information compared to *e.g.* radar and GPS studies like the one conducted by Marques *et al.* (2019) that involve a thorough analysis of horizontal avoidance but lack the assessment of vertical avoidance. Moreover, we make a comparison between the use of different height classes by three species, while most studies that analyse changes in height only compare the relative use of classes containing risk with that of classes bellow and over the turbines (Dahl *et al.*, 2013; Johnston *et al.*, 2014; Plonczkier & Simms, 2012).

Since birds seem to rely to some extent on vertical avoidance to prevent a risky approach to the turbines, this raises questions concerning whether and how the repowering of wind farms with higher wind turbines will impact birds' flight trajectories and represent a greater danger for birds, due to the occupation of areas where there was no risk previously (Smallwood, 2017). Some studies consider that higher and more spaced wind turbines may on the contrary reduce collision rates or have little effect on birds (Everaert, 2014; Marques *et al.*, 2014; Pearce-Higgins *et al.*, 2009). Therefore this is not a consensual subject and the effects will probably depend on site-specific factors (R. T. Watson *et al.*, 2018).

Birds that display horizontal avoidance are prone to be affected by displacement and barrier-effects (Desholm & Kahlert, 2005; Garvin *et al.*, 2011; Kelsey *et al.*, 2018; Masden *et al.*, 2009; Pearce-Higgins *et al.*, 2009). Barrier-effects are probably associated with energy costs, since birds change their flight route and increase the distance travelled. The cumulative effects of several wind farms that may lead to such a response may ultimately impact bird populations (Masden *et al.*, 2009). In migratory soaring bird species this is specially worrying, since these birds lose a lot of energy reserves during migration (Newton, 2008) and the energy demand that may result from avoiding several wind farms can make a difference in successfully reaching or not the migration destination. In the region of Sagres, there are several wind farms close to where BSJWF is located (APREN & INEGI, 2018). Therefore, it is possible that the migratory birds that cross the BSJWF suffer from cumulative effects even if they do not have a significant impact at the population level.

Finally, understanding how species-specific traits will affect avoidance behaviour is relevant to give insight on how birds may react to future mitigation measures and to select which measures may be applied to diminish the impact of wind farms on birds. This study provides this type of information including that regarding endangered species that occur in areas favoured for the construction of wind farms.

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4. Annex

Table 2: Number of selected movements for each species in each construction period.

Species	Number of selected movements		Total
	Pre	Post	
Booted Eagle	30	30	**60**
Griffon Vulture	30	30	**60**
Honey Buzzard	30	30	**60**
Black Stork	9	30	**39**
Egyptian vulture	8	30	**38**
Total	**107**	**150**	**257**

Table 3: Number of segments per height class and construction period within the 1km buffer, considering data of the three most represented species (Botted Eagle, Griffon Vulture and Honey Buzzard).

Height classes	Number of segments per height class and construction period in the 1km buffer		Total
	Pre	Post	
<20	5	4	9
20-60	17	12	29
60-100	22	26	48
100-200	36	43	79
200-500	18	39	57
>500	7	13	20
Total	105	137	**242**

Table 4: Number of segments per height class and construction period within the 1,5km buffer, considering data of the three most represented species (Botted Eagle, Griffon Vulture and Honey Buzzard).

Height classes	Number of segments per height class and construction period in the 1,5km buffer		Total
	Pre-construction	Post-construction	
<20	5	6	11
20-60	17	13	30
60-100	22	29	51
100-200	36	44	80
200-500	18	41	59
>500	7	13	20
Total	105	146	**251**

Table 5: Number of segments per height class in each construction period for the five species (Booted Eagle, Griffon Vulture, Honey Buzzard, Black Stork and Egyptian Vulture), within the 1km buffer.

Species	Height classes	Number of segments per species, height class and construction period in the 1km buffer		Total
		Pre	Post	
Booted Eagle	<20	3	2	5
	20-60	7	3	10
	60-100	11	9	20
	100-200	12	12	24
	200-500	2	12	14
	>500	0	4	4
Griffon Vulture	<20	1	1	2
	20-60	1	3	4
	60-100	4	9	13
	100-200	13	18	31
	200-500	12	20	32
	>500	6	6	12
Honey Buzzard	<20	1	1	2
	20-60	9	6	15
	60-100	7	8	15
	100-200	11	13	24
	200-500	4	7	11
	>500	1	3	4
Black Stork	High Risk	4	17	21
	Low Risk	5	24	29
Egyptian Vulture	High Risk	6	28	34
	Low Risk	5	15	20
Total		125	221	**346**

Table 6: Number of segments per height class in each construction period for the five species (Booted Eagle, Griffon Vulture, Honey Buzzard, Black Stork and Egyptian Vulture), within the 1,5km buffer.

Species	Height classes	Number of segments per species, height class and construction period in the 1,5km buffer		Total
		Pre	Post	
Booted Eagle	<20	3	2	5
	20-60	7	3	10
	60-100	11	10	21
	100-200	12	12	24
	200-500	2	12	14
	>500	0	4	4
Griffon Vulture	<20	1	3	4
	20-60	1	4	5
	60-100	4	11	15
	100-200	13	19	32
	200-500	12	22	34
	>500	6	6	12
Honey Buzzard	<20	1	1	2
	20-60	9	6	15
	60-100	7	8	15
	100-200	11	13	24
	200-500	4	7	11
	>500	1	3	4
Black Stork	High Risk	4	19	23
	Low Risk	5	26	31
Egyptian Vulture	High Risk	6	29	35
	Low Risk	5	16	21
Total		125	236	**361**

Table 7: Frequency of occurrence (number of movements) of flocking behaviour for each species.

Species	Type of flocking	Number of movements
Booted Eagle	Individuals	32
	Flocks 2-22 inds.	28
Griffon Vulture	Individuals	11
	Flocks 2-20 inds.	14
	Flocks 21-100 inds.	11
	Flocks 101-200 inds.	10
	Flocks 201-1000 inds.	14
Honey Buzzard	Individuals	45
	Flocks 2-6 inds.	15

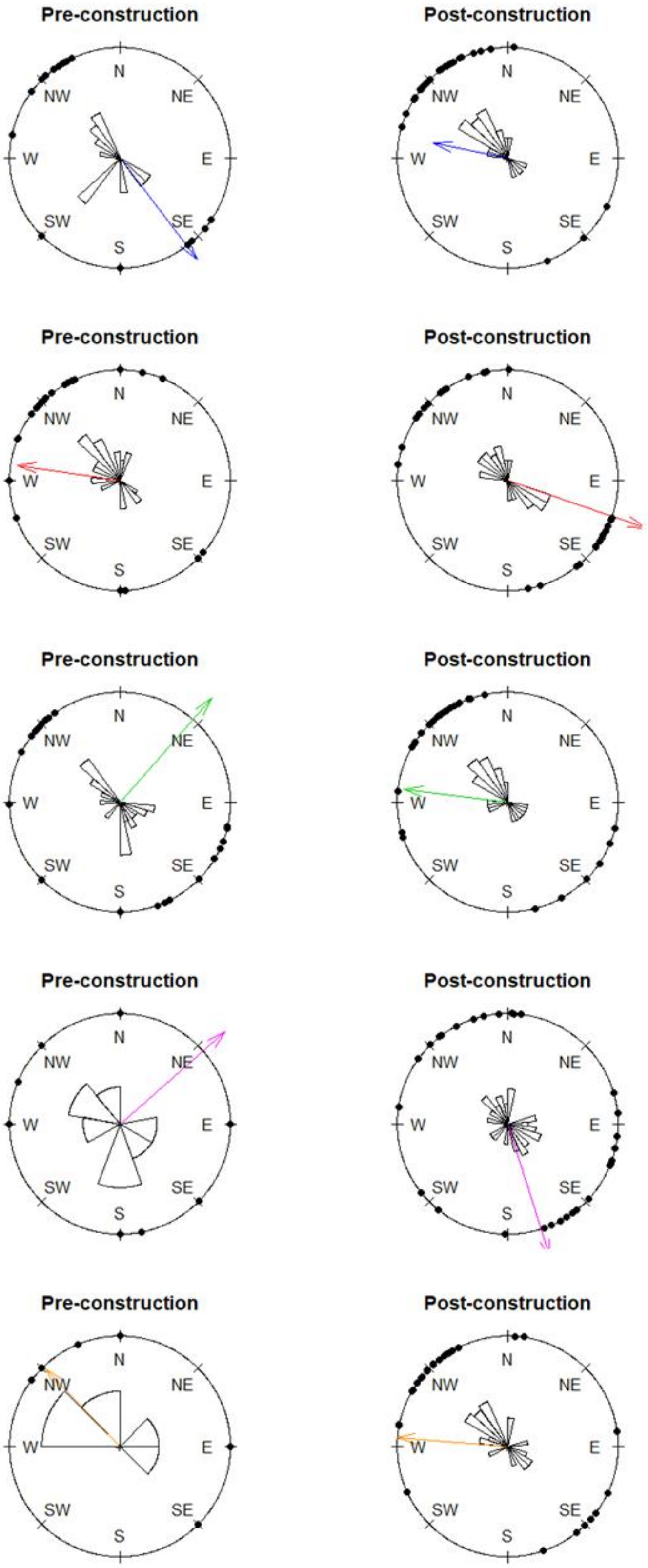

Figure 26: Distribution diagrams of wind directions and average wind direction (arrows) associated to the movements of, from top to bottom, Booted Eagle (blue arrow), Griffon Vulture (red arrow), Honey Buzzard (green arrow; n Pre = 30; n Post = 30, for these three species), Black Stork (lilac arrow; n Pre = 9; n Post = 30) and Egyptian Vulture (orange arrow; n Pre = 8; n Post = 30) for pre-construction (left) and post-construction (right) periods. Bar variation in the centre corresponds to a rose diagram of the frequency square root of each sector of wind direction. Arrows length represents the angular deviation: arrows near to the centre represent values close to 0 while arrows surpassing the circle represent values over 1.

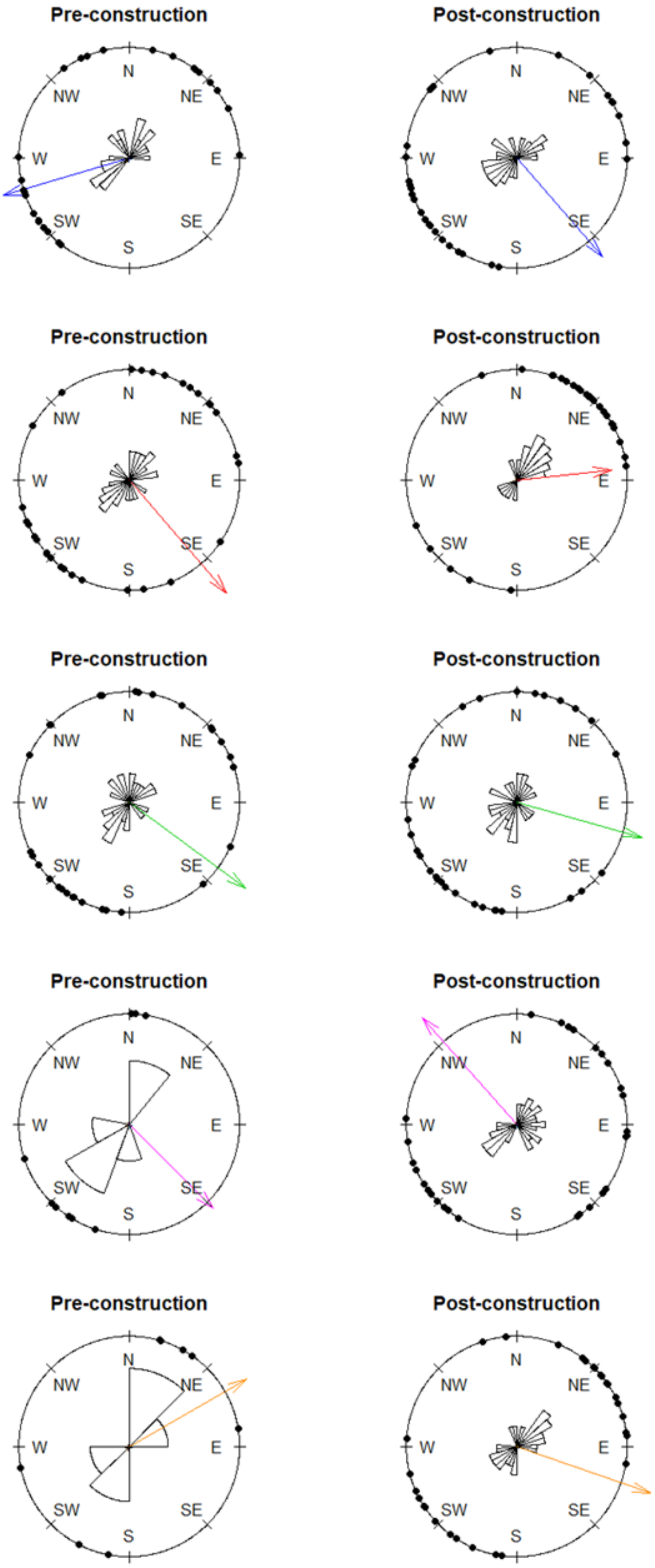

Figure 27: Distribution diagrams of wind directions and average wind direction (arrows) associated to the movements of, from top to bottom, Booted Eagle (blue arrow), Griffon Vulture (red arrow), Honey Buzzard (green arrow; n Pre = 30; n Post = 30, for these three species), Black Stork (lilac arrow; n Pre = 9; n Post = 30) and Egyptian Vulture (orange arrow; n Pre = 8; n Post = 30) for pre-construction (left) and post-construction (right) periods. Bar variation in the centre corresponds to a rose diagram of the frequency square root of each sector of wind direction. Arrows length represents the angular deviation: arrows near to the centre represent values close to 0 while arrows surpassing the circle represent values over 1.

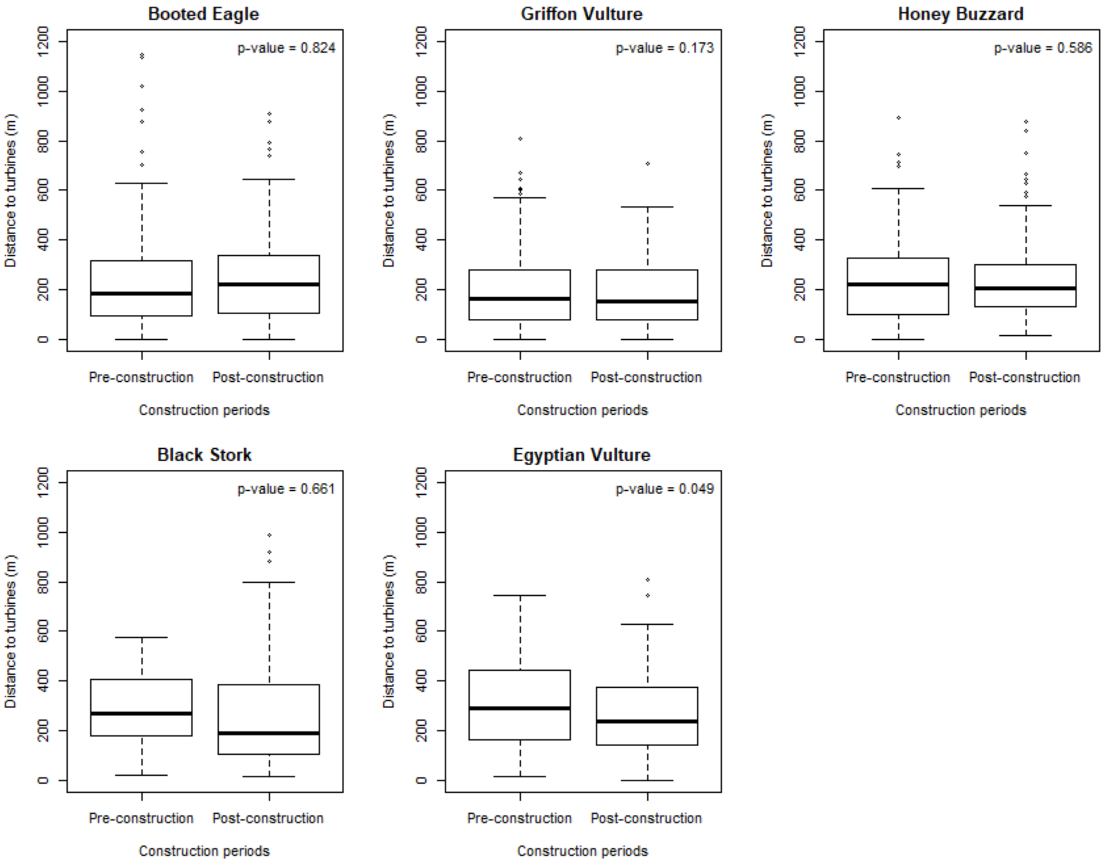

Figure 28: Differences in distance to turbines (m) between construction periods for both buffers (1km and 1,5km), in the movements of Booted Eagles, Griffon Vultures, Honey Buzzards (n Pre = 30; n Post = 30, for these three species), Black Storks (n Pre = 9; n Post = 30) and Egyptian Vultures (n Pre = 8; n Post = 30).

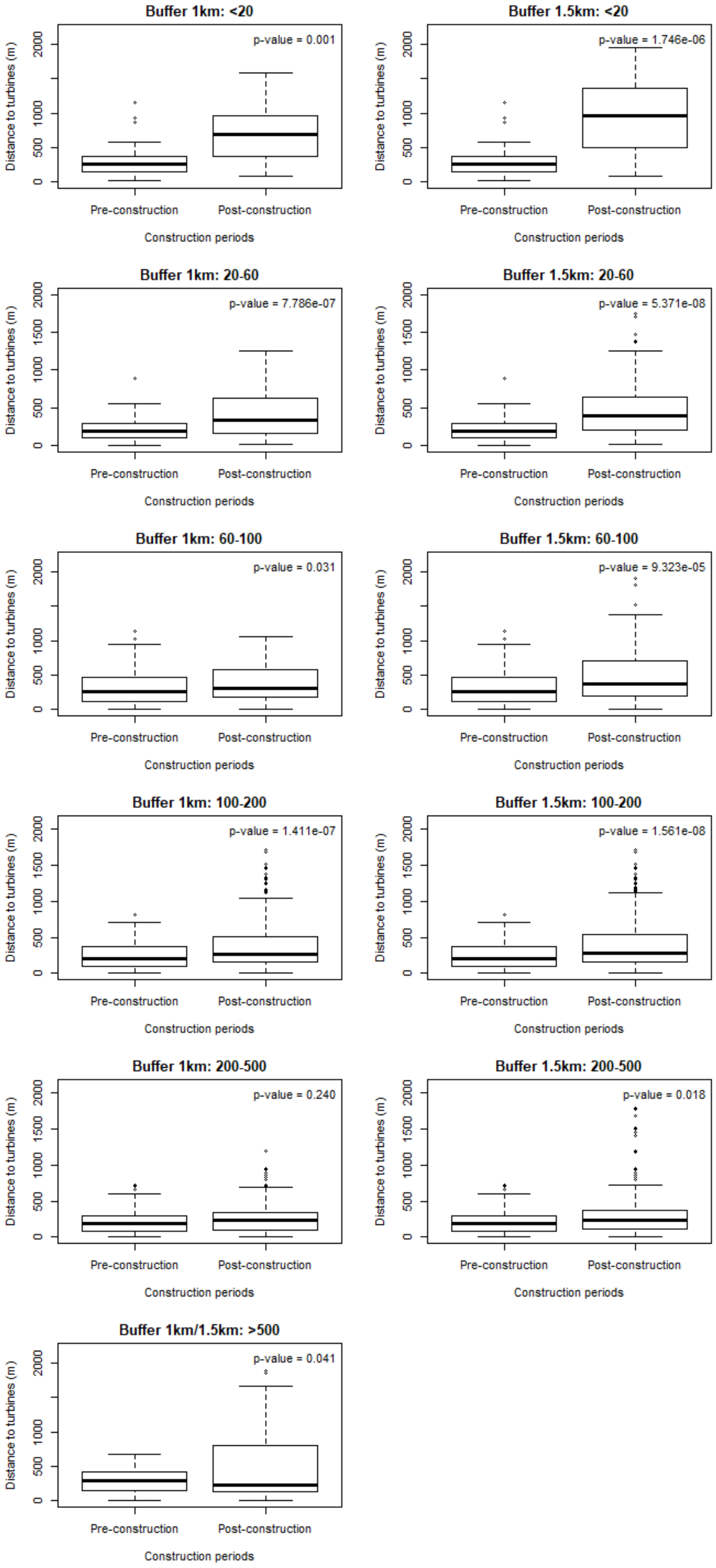

Figure 29: Differences in distance to turbines (m) between construction periods for movements of each height class for both buffers (1km and 1,5km). Number of segments (n) are represented in Table 3 and 4 in Appendixes.

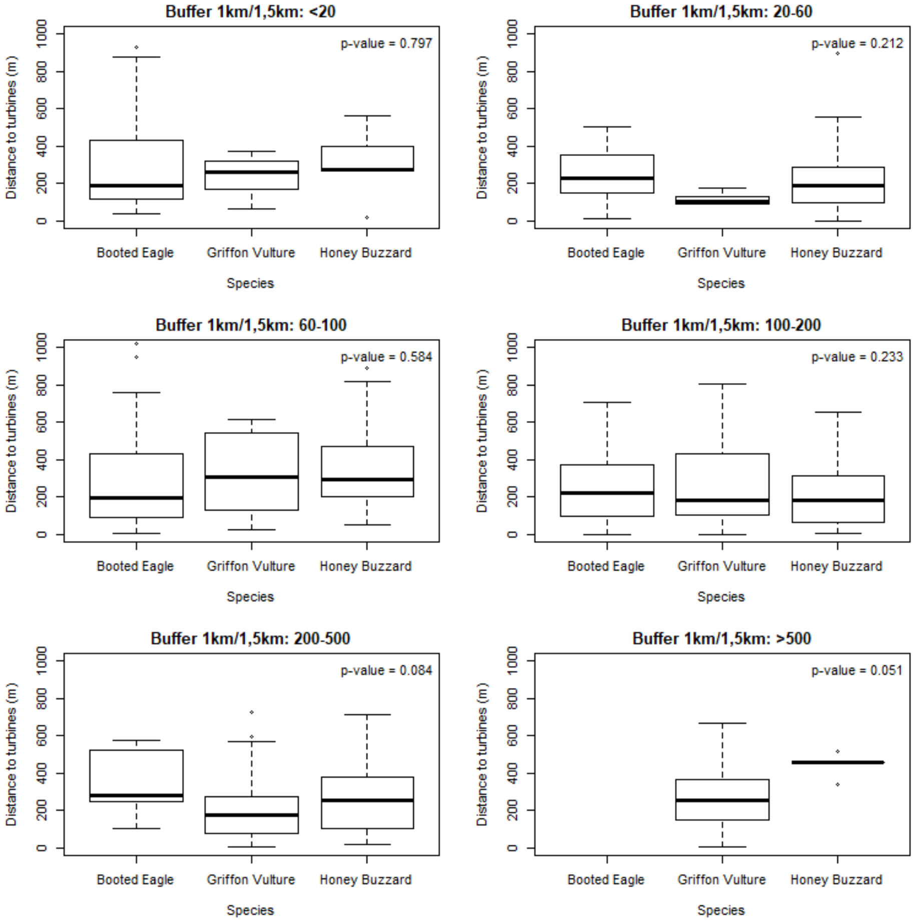

Figure 30: Differences in distance to turbines (m) between species for movements in pre-construction of each height class for both buffers (1km and 1,5km). Number of segments (n) are represented in Table 5 and 6 in Appendixes.

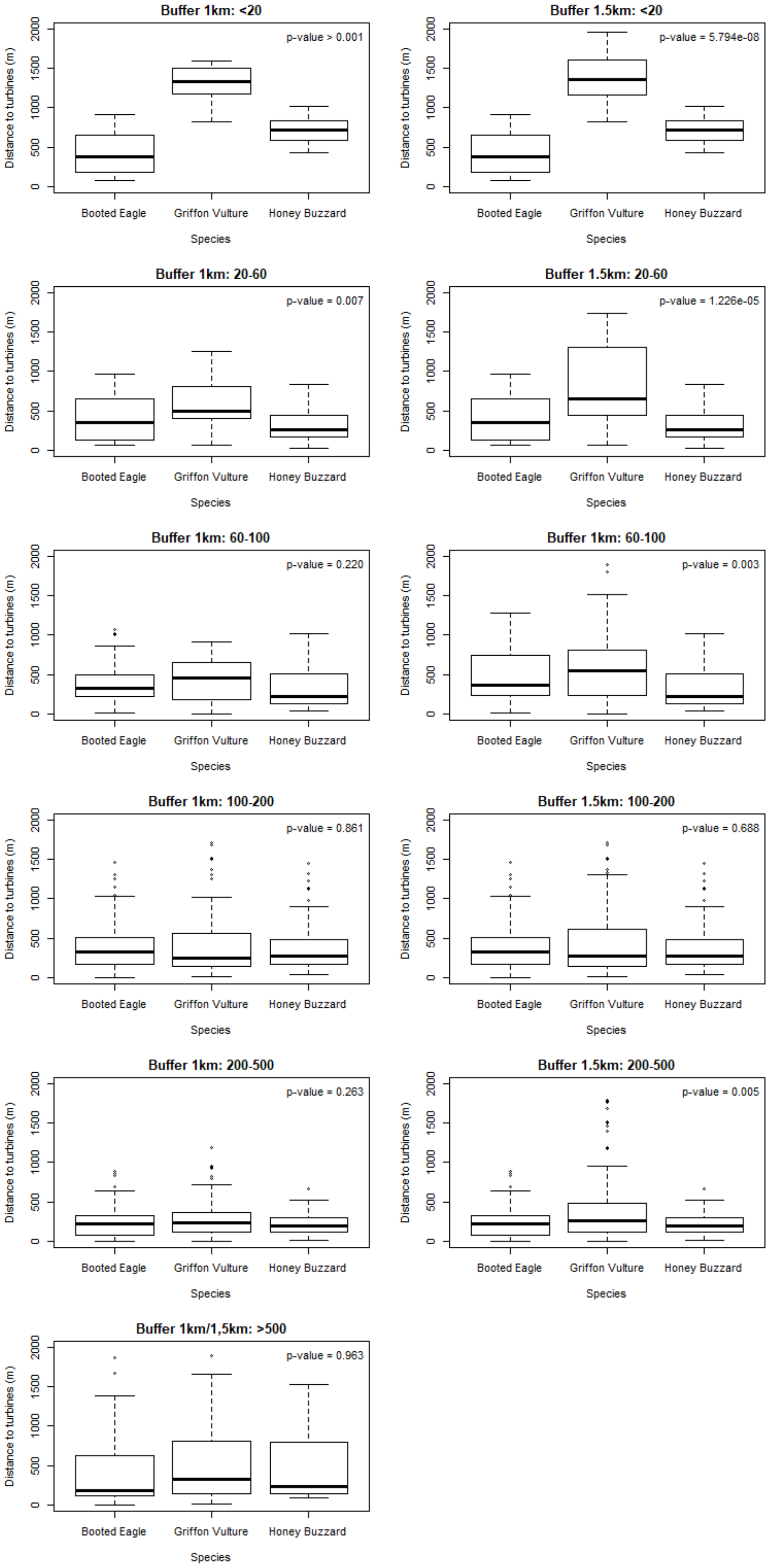

Figure 31: Differences in distance to turbines (m) between species for movements in post-construction of each height class for both buffers (1km and 1,5km). Number of segments (n) are represented in Table 5 and 6 in Appendixes.

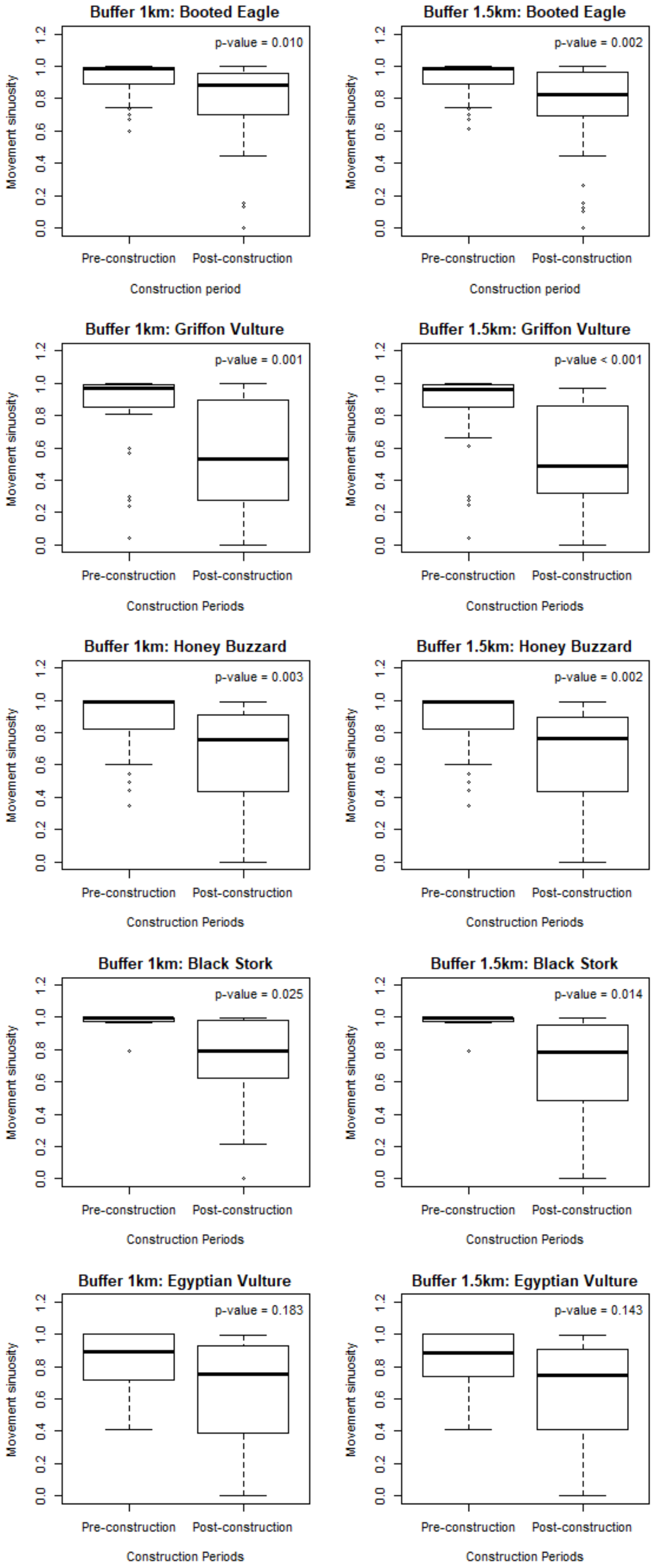

Figure 32: Differences in linearity between construction periods for movements within both buffers (1km and 1,5km) of Booted Eagles, Griffon Vultures, Honey Buzzards (n Pre = 30; n Post = 30, for these three species) , Black Storks (n Pre = 9; n Post = 30) and Egyptian Vultures (n Pre = 8; n Post = 30).

Table 8: Differences in proportion of movements for height classes and both buffers (1km and 1,5km) of the species Booted Eagle, Griffon Vulture, Honey Buzzard, Black Stork and Egyptian Vulture. The values were obtained represent the variation is use between the pre- and post-construction phases (see 2.3.5.2. Differences in flight altitude).

Species	Height classes	Difference in proportion for the 1km buffer (%)	Difference in proportion for the 1,5 km buffer (%)
Booted Eagle	<20m	-44.4	-45.7
	20-60m	-64.3	-65.1
	60-100m	-31.8	-26.0
	100-200m	-16.7	-18.6
	200-500m	400.0	388.4
	>500m	Only post-construction	Only post-construction
Griffon Vulture	<20m	-35.1	70.8
	20-60m	94.7	127.7
	60-100m	46.1	56.5
	100-200m	-10.1	-16.8
	200-500m	8.2	4.4
	>500m	-35.1	-43.1
Honey Buzzard	<20m	-13.2	-13.2
	20-60m	-42.1	-42.1
	60-100m	-0.8	-0.8
	100-200m	2.6	2.6
	200-500m	51.97	51.97
	>500m	160.5	160.52
Black Stork	High Risk	-6.7	-5.0
	Low Risk	0.5	4.0
Egyptian Vulture	High Risk	19.4	18.1
	Low Risk	-23.3	-21.8

Table 9: Estimators and p-values of permutation tests applied on height classes analyses.

Analyses		Buffer	Height Class	F	*P*
Comparison between construction periods		1km	<20	13.17	< 0.01
			20-60	26.72	< 0.01
			60-100	4.69	0.03
			100-200	28.75	< 0.01
			200-500	1.38	0.24
			>500	4.31	0.04
		1.5km	<20	28.90	< 0.01
			20-60	32.86	< 0.01
			60-100	15.77	< 0.01
			100-200	33.34	< 0.01
			200-500	5.68	0.02
			>500	4.31	0.04
Comparison between construction periods for each species	**Booted Eagle**	1km	<20	0.38	0.55
			20-60	8.05	0.01
			60-100	4.68	0.03
			100-200	11.81	<0.01
			200-500	0.98	0.33
			>500	—	—
		1.5km	<20	0.38	0.55
			20-60	8.05	0.01
			60-100	10.17	<0.01
			100-200	11.81	<0.01
			200-500	0.98	0.33
			>500	—	—
	Griffon Vulture	1km	<20	50.77	<0.01
			20-60	9.23	0.01
			60-100	1.76	0.19
			100-200	6.33	0.01
			200-500	4.97	0.03
			>500	5.53	0.02
		1.5km	<20	61.38	<0.01
			20-60	9.35	0.01
			60-100	6.16	0.02
			100-200	9.63	<0.01
			200-500	11.01	<0.01
			>500	5.53	0.02
	Honey Buzzard	1km	<20	9.71	0.01
			20-60	5.47	0.02
			60-100	0.01	0.75
			100-200	13.42	<0.01
			200-500	1.03	0.32
			>500	0.05	0.82
		1.5km	<20	9.71	0.01
			20-60	5.47	0.02

			60-100	0.01	0.75
			100-200	13.42	<0.01
			200-500	1.03	0.32
			>500	0.05	0.82
Comparison between species for each construction period	**Pre-construction**	1km	<20	0.26	0.77
			20-60	1.58	0.21
			60-100	0.54	0.58
			100-200	1.47	0.23
			200-500	2.56	0.08
			>500	4.11	0.05
		1,5km	<20	0.26	0.77
			20-60	1.58	0.21
			60-100	0.54	0.58
			100-200	1.47	0.23
			200-500	2.56	0.08
			>500	4.11	0.05
	Post-construction	1km	<20	14.93	<0.01
			20-60	5.48	0.01
			60-100	1.53	0.22
			100-200	0.15	0.86
			200-500	1.34	0.26
			>500	0.04	0.96
		1.5km	<20	32.89	<0.01
			20-60	13.65	<0.01
			60-100	6.187	<0.01
			100-200	0.38	0.69
			200-500	5.52	0.01
			>500	0.04	0.96

Table 10: Estimators and p-values of permutation tests applied on linearity analyses.

Analyses			**Buffer**	**F**	***P***
Comparison between construction periods			1km	33.94	<0.01
			1.5km	45.11	<0.01
Comparison between construction periods for each species	**Black Stork**		1km	5.43	0.03
			1.5km	6.70	0.01
	Booted Eagle		1km	7.178	0.01
			1.5km	11.09	<0.01
	Egyptian Vulture		1km	1.85	0.18
			1.5km	2.24	0.14
	Griffon Vulture		1km	12.35	<0.01
			1.5km	16.76	<0.01
	Honey Buzzard		1km	9.99	<0.01
			1.5km	10.81	<0.01
Comparison between species for each construction period	**Pre-construction**		1km	1.33	0.27
			1.5km	1.25	0.29
	Post-construction		1km	2.89	0.06
			1.5km	2.80	0.07
Comparison between construction periods for each flock	**Booted Eagle**	Individuals	1km	0.06	0.81
			1.5km	0.77	0.39
		Flocks	1km	7.97	0.01
			1.5km	8.04	0.01

	Griffon Vulture	Individuals	1km	0.25	0.63
			1.5km	0.10	0.76
		Flocks [2,20]	1km	5.67	0.04
			1.5km	8.87	0.01
		Flocks [21,100]	1km	0.56	0.48
			1.5km	0.60	0.46
		Flocks [101,200]	1km	4.91	0.06
			1.5km	6.72	0.03
		Flocks [201,1000]	1km	10.90	0.01
			1.5km	13.73	<0.01
	Honey Buzzard	Individuals	1km	5.01	0.03
			1.5km	5.75	0.02
		Flocks	1km	4.90	0.05
			1.5km	4.87	0.05