Highest-altitude wind turbine in Europe, Gries, Valais, Switzerland, 2’465 m

Large soaring raptors vs wind turbines development in the Swiss Alps

Final report, January 2023

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ECOLOGY & EVOLUTION
CONSERVATION BIOLOGY

TABLE OF CONTENTS

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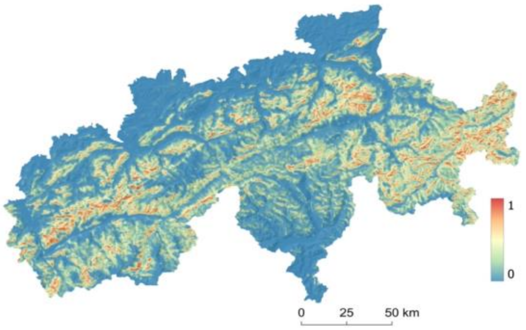
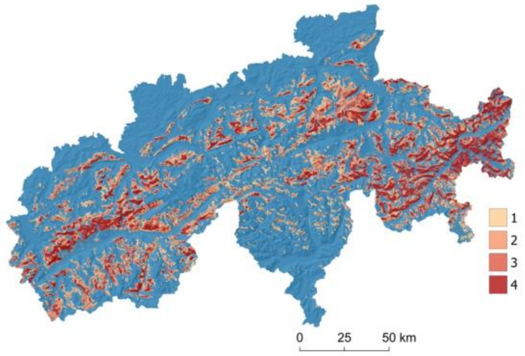
GRAPHICAL ABSTRACT: HOW TO USE THE HIGH-RISK CONFLICT MAPS OF THIS REPORT

A wind turbine is planned in a specific location in the Alps: does the foreseen installation site overlap with bearded vulture and/or golden eagle critical habitat?

Bearded vulture
Swiss Alps

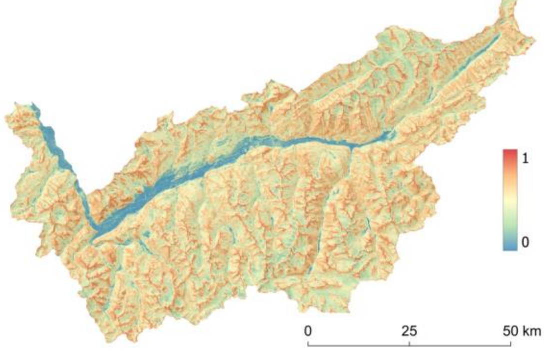


1. Click on this map to evaluate what is the probability, at a foreseen installation site, that bearded vultures engage in low altitude flights (<200 m above ground level), which represents a potential risk of collision with wind turbine blades.

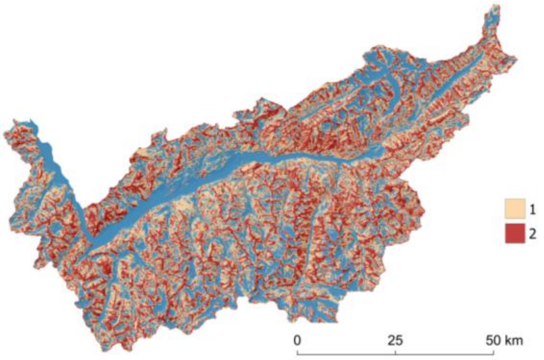


2. Click on this map to evaluate the level of risk for bearded vulture conservation (from moderate in peach-orange to high in red) of installing a wind turbine at a foreseen site.

Golden eagle
Valais



1. Click on this map to evaluate what is the probability, at a foreseen installation site, that golden eagles engage in low altitude flights (<200 m above ground level), which represents a potential risk of collision with wind turbine blades.



2. Click on this map to evaluate the level of risk for golden eagle conservation (from moderate in peach-orange to high in red) of installing a wind turbine at a foreseen site.

Coloured areas should be avoided from the perspective of the conservation of the two species, meaning wind turbine installation should be planned in the areas highlighted in blue.

After selecting non-risky zones for bearded vulture and golden eagle, it is still necessary to perform an environmental impact assessment according to Swiss Environmental legislation.

INTRODUCTION

Large soaring raptors vs wind turbines development in the Swiss Alps is an applied research project launched by the Division of Conservation Biology, University of Bern, in autumn 2014. The project's main objectives were to develop spatially-explicit models that may assist governmental agencies and non-governmental associations in their decision-making process regarding the suitability of foreseen locations for the installation of wind turbines from the viewpoint of the conservation of raptors, which are key elements of Alpine biodiversity. The idea is to avoid as much as possible potential airspace conflicts between large soaring raptors and future wind energy development. A recent Europe-wide study ranked Switzerland among the countries with the lowest *per capita* wind energy production (Iten & Nipkow, 2019) but the Swiss government has planned to boost this industry, via massive subsidies, with the objective to reach a wind electricity production of 4,3 TWh by 2050 (Bundesamt für Raumentwicklung ARE, 2020), compared to a present day production of around 0.14 TWh. Numerous new wind turbine projects are thus expected in the coming years but their deployment, in particular in fragile high-altitude ecosystems harbouring emblematic biodiversity, might impact not only valuable habitat but could also increase the mortality of Alpine birds and bats colliding with the rotor blades. Our research focuses on two of the principal large resident raptor species in the Swiss Alps, namely the bearded vulture (*Gypaetus barbatus*) and the golden eagle (*Aquila chrysaetos*). These two species are at particular risk of collision with the wind turbine blades due to their large home ranges and extensive daily movements. Moreover, their late sexual maturity and low breeding rate render them particularly vulnerable from a population dynamic viewpoint. As demonstrated by Schaub et al. (2009), a slight increase in annual mortality rate of only 60% would lower the survival rate of bearded vultures to a degree that would threaten the reintroduced Alpine population with extinction in the mid and long term. A re-actualisation of the model (Schaub et al., in prep.) with more recent data showed a similar pattern. The current Alpine population of the bearded vulture numbers in the 300 individuals and faces an average annual survival rate of 95%. This means that this population currently loses 15 individuals per year. An increase by 60% of the present day mortality would mean that nine additional losses per year would put the population at extinction

risk. In other words, if all the wind turbines installed in the entire Alpine massif would kill nine bearded vultures a year, the population would be doomed in the long run as it would start to progressively decline to extinction.

Hazardous airspace conflicts are expected to occur if wind energy facilities are constructed in topographic situations frequently overflown by the birds. The deliverables of this study are predictive maps of raptors’ space use that rank Alpine geographic areas according to the probability of occurrence of these two species of raptors. In the following sections we present the main achievements of our two research modules. The first section deals with the bearded vulture and the second with the golden eagle. A graphic abstract at the very beginning of this report shows how these materials should be used by governmental agents, policy-makers, land planners, promoters, and nature and bird protection associations.

MODULE 1

PREDICTING AREAS OF POTENTIAL CONFLICTS BETWEEN BEARDED VULTURES *(GYPAETUS BARBATUS)* AND WIND TURBINES IN THE SWISS ALPS

The bearded vulture module started in November 2017 with the aim of modelling the species’ potential distribution and flight behaviour to identify areas where conflicts between the conservation of this species and the development of wind energy may arise. During the first part of this module the focus was on re-assessing the ecological requirements of the species and refine the predictions regarding its potential distribution across the Swiss Alps, in line with what Hirzel et al. (2004) had done for Valais, but encompassing the whole Swiss alpine range and relying on a much larger and updated dataset. These results served as a basis for the second part of this module that focused on the species’ flight altitude behaviour. Using data collected from GPS-tagged birds, we identified the environmental variables that drive low-altitude flights and predicted the areas within the Swiss alpine range where bearded vultures are likely to fly below 200 m altitude, i.e. within the rotor-swept zone of modern horizontal axis wind turbines.

The main achievements obtained in this module are:

1. The compilation of a reliable database of bearded vulture observations across the Swiss Alps, including their classification in different age groups.
2. The preparation of suitable datasets concerning the environmental predictors to model the species potential distribution and its flight behaviour in the Swiss Alps. These data were also crucial for the second module where they have been used in several analyses.
3. A spatially-explicit model of habitat suitability for the bearded vulture across the Swiss Alps.
4. The elaboration of new methodological approaches for performing statistical analyses similar to the one presented at point 3.
5. A spatially-explicit model of the species' flight altitude behaviour within the Swiss alpine range.

All the above-mentioned results are included in the PhD thesis of Dr Sergio Vignali, which is attached as appendices to this report. Specifically, the habitat suitability model (point 3) is part of the first chapter and has been published in the journal *Global Ecology and Conservation* in 2020 and is entitled *Modelling the habitat selection of the bearded vulture to predict areas of potential conflict with wind energy development in the Swiss Alps* (Vignali, 2021). The methodological statistical approaches (point 4) are included in the second chapter of the PhD thesis and have been described and published in the journal *Ecology and Evolution* in 2020: *SDMtune: An R package to tune and evaluate species distribution models* (Vignali et al., 2020). Finally, the analysis of the flight altitude behaviour (point 5) is included in the third chapter of the PhD thesis and has been published in a revised format in the journal *Royal Society Open Science* in 2022: *A predictive flight-altitude model for avoiding future conflicts between an emblematic raptor and wind energy development in the Swiss Alps* (Vignali et al., 2022).

While the output of the first model (point 3) identifies, on a broad-scale, areas where environmental conditions are favourable to the bearded vulture, the second model (point 5) refines its prediction by including a vertical component (flight altitude), in order to generate a quasi 3D model. The latter model provides the spatial probability that bearded vultures fly within their habitat at a dangerous altitude and identifies areas to which particular attention should be paid from the perspective of wildlife-friendly wind turbine planning (Fig. 1 and 2).

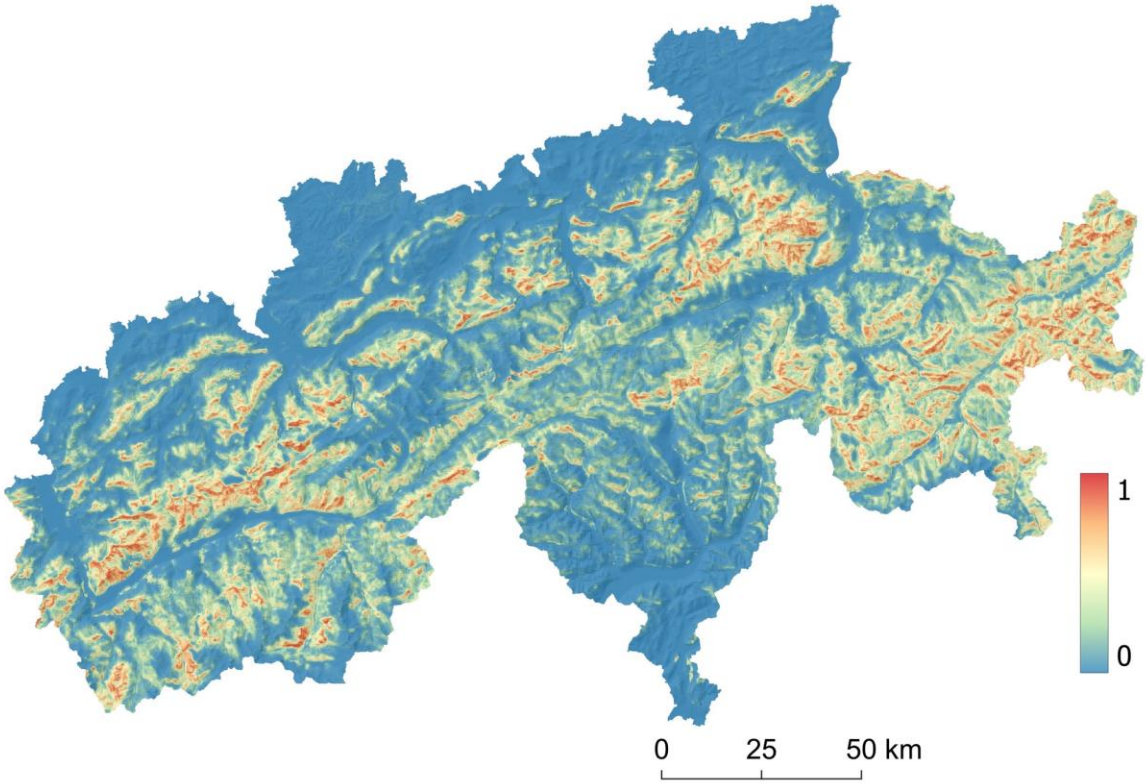


Figure 1: Predicted probability of a bearded vulture flying below 200 m a.g.l. within its habitat extrapolated to the Swiss Alps. The probability is shown as a gradient ranging from blue (zero probability) to red (high probability). Drawn from Fig. 3c in Vignali et al. (2022).

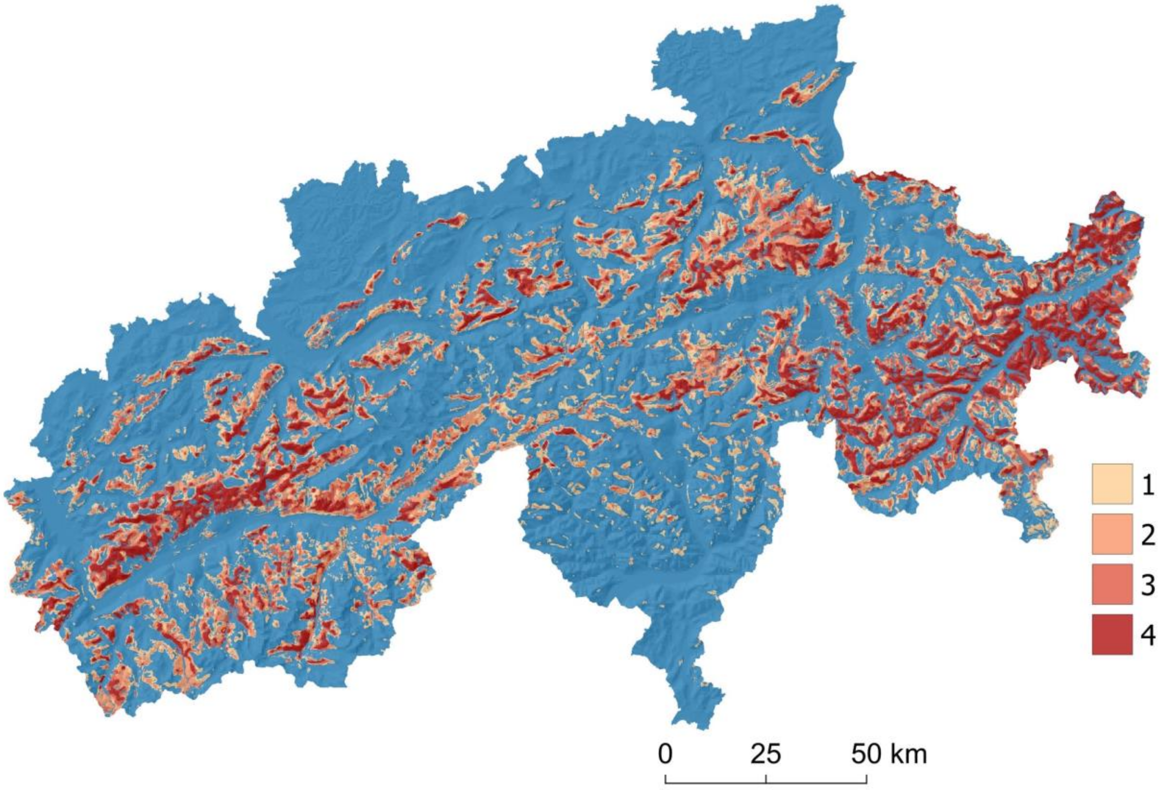


Figure 2: High-risk conflict map delineating the areas where major conflicts are expected, with colours showing different grades of «sensitivity» of a given area from the perspective of bearded vulture conservation. Drawn from Fig. 3f in Vignali et al. (2022).

Both models developed in this module provide a general framework that could be applied for assessing potential conflicts between the development of wind energy and raptor species in general. Although they have been developed for Switzerland, they can easily be extended to other European Alpine countries for which similar spatial data are available. Moreover, the model outputs provide sound fundamentals for the required impact assessments for proper wind turbine planning and inform wind energy companies about the zones where major conflicts with raptor conservation are likely to occur so that a strategic choice of installation sites is performed prior to any financial investments being consented.

MODULE 2

PREDICTING SPACE USE AND FLIGHT BEHAVIOUR OF GOLDEN EAGLES (*AQUILA CHRYSAETOS*) IN THE SWISS ALPS TO MITIGATE AIRSPACE CONFLICTS WITH WIND ENERGY DEVELOPMENT

The golden eagle module was officially launched in March 2018. In the early phase of this module the focus was on collecting high-resolution spatial data on the eagles’ movements and flight behaviour across the Valais Alps. The data collected during this period have been used to 1) compare two methods adopted to collect the data on eagle movements, 2) study the flight behaviour of the eagles and link the different flight behavioural states to terrain characteristics, and 3) develop a spatially-explicit quasi 3D model of space use similar to the one built for the bearded vulture.

The main achievements obtained in this module are:

1. A trapping campaign to capture and GPS-tag golden eagles.
2. A trial to compare two tracking technologies, namely the direct visual characterisation of flight relying on laser rangefinder binoculars and the remote tracking of eagles equipped with GPS transmitters The idea here was to evaluate the quality of the acquired data in the context of studying the species’ flight behaviour.

3. The development of a Shiny web application (Chang et al., 2023) to facilitate the classification of flight tracks in different behavioural states (e.g. soaring, gliding, direct flight).
4. A first analysis of different flight behavioural states in relation to terrain characteristics.
5. A spatially-explicit model of the species' flight altitude behaviour within the Valais Alps.

The comparison of the two technologies (point 2) was conducted by Ron Milgalter, a former PhD candidate in our group. A description of the method is presented below (laser rangefinder). Unfortunately, Ron Milgalter decided to quit the project in October 2019 and a document highlighting his main findings is still pending. The remaining part of the research of this module was carried out by Dr Sergio Vignali who took over the analysis of the data after concluding his PhD on the first module (bearded vulture). The developed Shiny web application *anntrack* (point 3) has been used to classify the data collected by GPS-tagged eagles into different flight behaviours. This was the basis to study how certain flight behaviours that pose eagles at higher risk of collision with future wind turbines (i.e. thermal and orographic soaring) are related to specific terrain characteristics. The main findings of this analysis (point 4) are included in the Bachelor thesis of Anita Schmid and attached as appendices to this report. Finally, the outputs of the spatially-explicit model of the flight altitude behaviour (point 5) are described below. They still ought to be published in peer-review journals.

DATA COLLECTION

GPS Tags

The field operation to trap adult golden eagles began on November 5th, 2018 under the supervision of Stéphane Mettaz, field technician in our research group, assisted by Anna Sandor and Ron Milgalter, and ended on February 5th, 2020. Eagles were captured using custom-made bow-net traps that were positioned along south-facing slopes within their territories throughout the Valais and baited with animal carrion. The trapping system was equipped with a trigger releasing the armed trap through a radio signal (see Bloom et al., 2007) that could be emitted from a distance of up to 3-4 km, and complemented with wireless

cameras that were sending real time images of the trap site over email when a movement and change in temperature (i.e. presence of an animal generating heat radiation) was detected in the immediate vicinity of the trap. Fifteen eagles were trapped in total, including two immatures (second and third year, respectively) and a sub-adult. At each capture, morphological measurements were conducted to estimate the eagle's age (Bloom & Clark, 2001) prior to outfitting it with a solar-powered GPS-GSM tag (Ornitela OT 50B 3G). The tag delivered location data twice a day through the GPRS network, including information about the GPS 3D position, above-sea-level altitude, flight speed and direction, as well as instant flight acceleration that reveals bird activity.

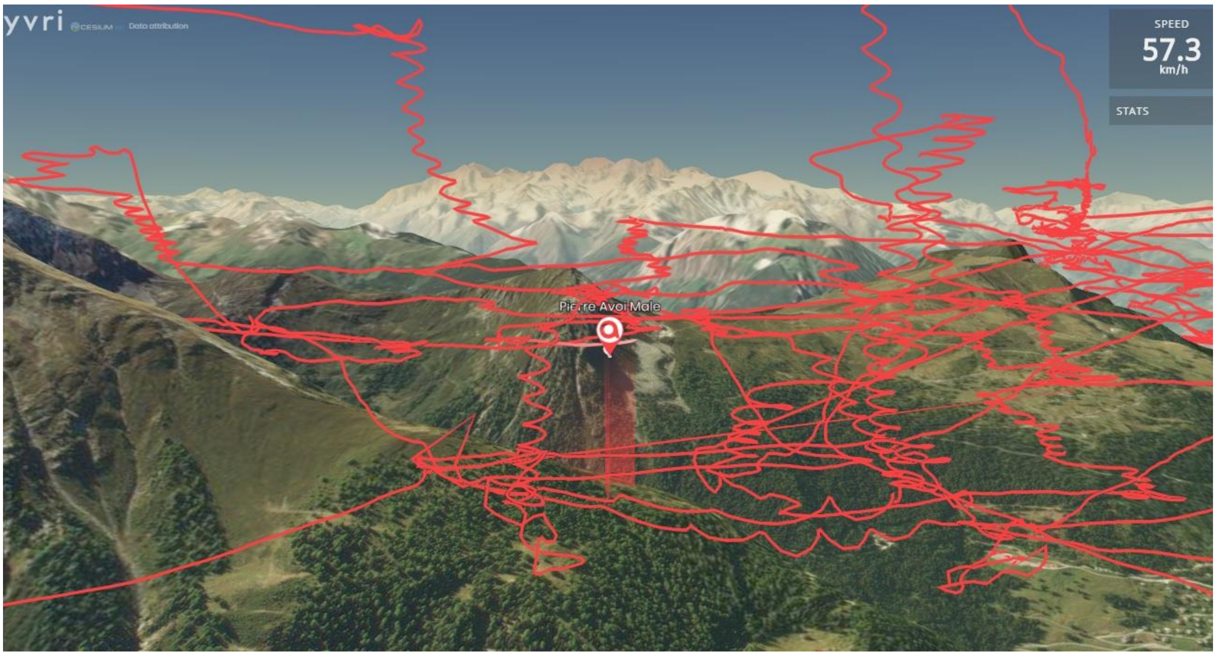


Figure 3: Illustration of high temporal resolution data (1 Hz) of one of the eagles collected when the Flight Detection Feature was activated.

After releasing an eagle, the bird's locations were obtained usually twice a day (normal monitoring) while fine-grained behaviour data were collected at a resolution of 1 Hz (i.e., one GPS fix per second) on pre-selected days (as high resolution data collection drains tag battery, this could not be performed on a daily basis), using the Flight Detection Feature of the tag, which is a highly energy efficient feature that activates when the eagle is engaged in active flight (Fig. 3). High resolution data sampling was conducted from dawn to dusk during both good and bad weather days so as to obtain a balanced sample representing

both nice and adverse weathers conditions. As per 31 December 2022, 13,076,831 GPS locations had been collected from the tagged eagles, of which 96.2% were at high temporal resolution (1 Hz).

Laser rangefinder

The methodology used was based on a pilot study conducted in April-May 2017, in which flight behaviour data were collected in 30+ eagle territories (3,500 observed locations comprising 128 individual flight tracks). Prior to the fieldwork, a stratified sampling design was prepared, to collect a balanced set of data for three different periods of the eagles' annual life cycle, namely breeding, dispersal, and wintering. This design, formulated in ArgGIS, stratified the canton of Valais according to different combinations of selected strata, which were assumed to influence the eagles' flight behaviour and included wind speed (i.e. high, medium, and low wind speed) and aspect (i.e. south-facing, north-facing, and west/east facing slopes).

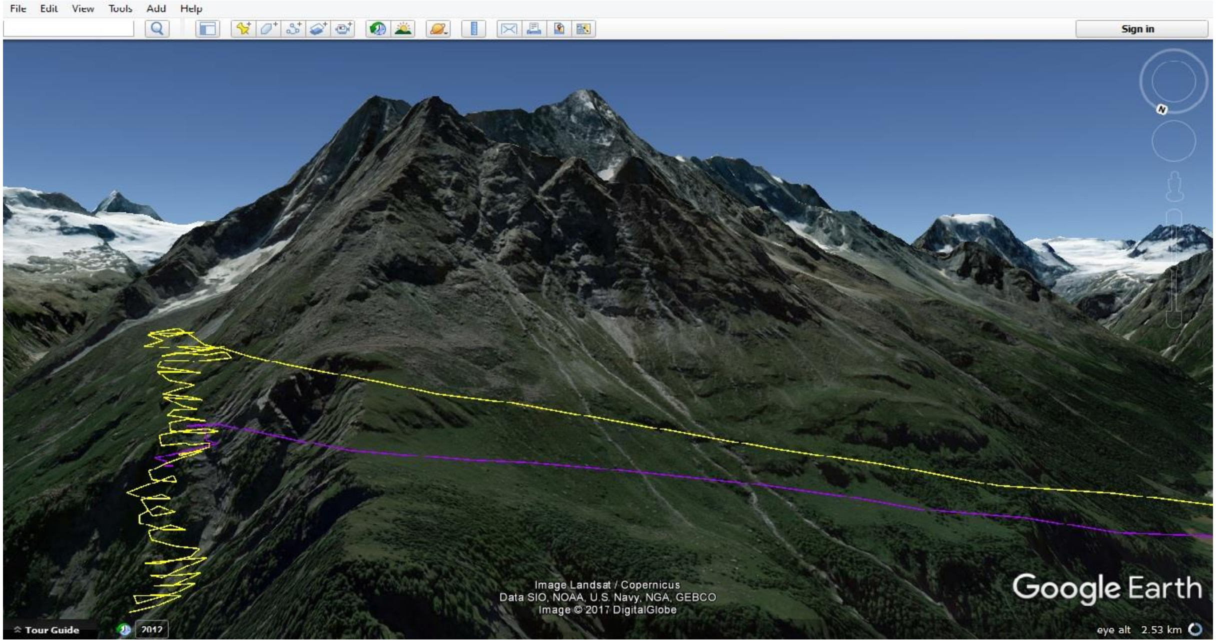


Figure 4: Example of a flight track of a golden eagle reconstituted from data collected with the rangefinder Vectronix Vector 21 Aero (the purple curve shows the corrected locations).

Survey sites were randomly generated within each combination of the strata throughout Valais. At a given survey site, high-resolution data were collected from observed eagles for a period of 3 h, using a binocular rangefinder (Vectronix Vector 21 Aero) with an integrated 3-dimensional, 360° digital compass, a precision-guided laser, and an inclinometer. The recorded variables included real distance from observer, azimuth, and inclination angle, which were all automatically logged into a field laptop using a custom-made software. During the fieldwork period, 26,000 observed in-flight locations were acquired, comprising 650 individual flight tracks (Fig. 4).

LASER RANGEFINDER VS GPS TELEMETRY COMPARISON

In order to facilitate the comparison of the two methods and apparatus used to collect flight behaviour data, territories of tagged eagles were surveyed between June 23 and July 11 2019. Each territory was surveyed in different locations and the Flight Detection Feature of the eagle associated with a given territory was turned on. Preliminary analysis showed that the data acquired by the two apparatus were highly overlapping in terms of accuracy of altitude estimation, flight structure, and position, with variation of only a few meters (however, a correction of a relatively constant azimuth reading was needed; see Fig. 4).

FLIGHT ALTITUDE MODEL

Using the data collected by the GPS-tagged golden eagles we built a spatially-explicit model to predict were eagles are likely to fly below the critical altitude of 200 m a.g.l. Flights occurring below this altitude pose eagles at high risk of collision because they might intersect the rotor-swept area of modern wind turbines. The methodological approach and the data cleaning process used for this analysis followed what we have done in the first module of this research project for the bearded vulture, and are described in Vignali et al. (2022).

We started from the GPS data available as per 31 December 2022. Note that not all tracked golden eagles delivered data until that date because of tag failure or loss, or death of the eagle. Altogether, we obtained data from 14 individuals. The raw data were submitted to a series of cleaning steps to reduce the position error and guarantee that they were collected when the bird was

flying. First, all GPS fixes collected outside the Swiss Alpine range were removed (mainly occurring on the Italian territory) as well as those with a large position error (HDOP≥10, Katzner et al. (2012)) or considered to hold an inaccurate flight altitude measurement – i.e. flight altitude a.g.l. < -50m or ≥ 4,000m (Poessel et al., 2018). In a second step, GPS locations collected during night or considered to be not in flight (instantaneous ground speed < 2m/s with flight altitude < 100 m a.g.l., Poessel et al. (2018)) were removed, obtaining a sample of 10,117,696 GPS locations of which 66% were collected below 200 m a.g.l. (average proportion varying among birds from 51.4% to 76.4%, Table 1). Finally, in the case of high temporal resolution data, we sampled one observation per minute to avoid an overrepresentation of the data collected when the flight detection feature was active. The final dataset used to model the flight altitude behaviour included 227,666 GPS locations.

The environmental variables used to train the model were the same included in the model developed for the bearded vulture (Vignali et al., 2022) with the exception of those representing food availability, which were not considered here. Ibex and chamois are effectively only a secondary food source for adult golden eagles, eaten mainly as carrion or hunted as bucklings and doelings, while the main prey from April to October is represented by marmots (Pedrini & Sergio, 2002) for which no spatial information was available.

The developed model was able to accurately predict the probability of eagles flying below the critical altitude of 200 m a.g.l. This was highlighted by the fairly high AUC values (0.74 and 0.73 for training and validation datasets, respectively) (Hosmer & Lemeshow, 2000), which were similar to those obtained for the bearded vulture in Switzerland (Vignali et al., 2022) and South Africa (Reid et al., 2015). Moreover, the model had good ability to generalise across birds (Table 2) and different regions of the study area (Table 3).

Table 1: Data on GPS-tagged golden eagles used to model the flight altitude with sex (M: male; F: female), estimated age at capture, per cent of locations below 200 m.a.g.l. (%), number of GPS locations retained after data cleaning (*N*) and subsampling one location per minute (*S*), date of the first (start) and last (end) GPS fix after data cleaning, total number of tracking days within the Swiss alpine range and inter-fix interval (in seconds) given as median, and minimum-maximum range.

Bird ID	Sex	Age	%	N	S	Start	End	Days	Inter-fix interval
182238	M	Adult	61.9	167,935	4,762	12 Nov 2018	08 Aug 2019	227	60 (60–28,785)
182239	M	Adult	63.5	2,060,648	43,990	20 Nov 2018	09 Apr 2022	1,196	60 (60–46,806)
182240	F	Adult	57.8	1,304,721	29,380	22 Nov 2018	31 Dec 2022	1,437	60 (60–43,223)
182241	F	Sub-adult	67.8	1,996,562	42,601	17 Nov 2018	31 Dec 2022	1,458	60 (60–43,209)
182242	F	Adult	69.0	352,864	7,528	19 Jan 2019	01 Dec 2019	287	60 (60–43,262)
182243	M	Adult	53.3	200,633	4,158	23 Jan 2019	15 Aug 2019	154	60 (60–36,034)
182244	F	Adult	61.0	33,352	752	26 Jan 2019	19 Feb 2019	24	60 (60–18,009)
182245	M	2nd year	60.2	838,976	19,380	22 Nov 2018	31 Dec 2022	1,143	60 (60–46,820)
182246	M	3rd year	76.4	235,254	5,749	31 Jan 2019	26 Dec 2022	491	60 (60–50,393)
182247	M	Adult	57.1	1,867,260	38,158	05 Feb 2019	31 Dec 2022	1,345	60 (60–46,788)
183006	M	Adult	51.4	432,170	9,204	07 Feb 2020	11 Dec 2022	673	60 (60–46,791)
183008	F	Adult	56.5	155,046	2,882	14 Feb 2019	24 Mar 2019	39	60 (60–25,190)
183010	M	Adult	53.5	270,879	6,102	27 Feb 2019	13 Mai 2019	76	60 (60–36,070)
183012	F	Adult	58.0	201,396	4,170	23 Nov 2019	14 Oct 2021	300	60 (60–43,675)

Table 2: Model evaluation based on a leave-one-bird-out cross validation. Each model was trained with GPS locations of all but one bird and evaluated with the held apart locations of the respective bird. Each line reports the ID of the excluded bird and the AUC values of the training and testing datasets, respectively (in parenthesis the number of GPS locations included in each dataset).

Bird ID	Training AUC	Testing AUC
182241	0.723 (N=183,607)	0.730 (N=44,059)
182239	0.734 (N=182,480)	0.711 (N=45,186)
182245	0.721 (N=207,143)	0.685 (N=20,523)
182242	0.732 (N=219,851)	0.698 (N=7,815)
183010	0.728 (N=221,488)	0.686 (N=6,178)
183012	0.732 (N=223,196)	0.678 (N=4,470)
182238	0.721 (N=222,677)	0.693 (N=4,989)
182247	0.715 (N=188,163)	0.754 (N=39,503)
182246	0.726 (N=221,426)	0.676 (N=6,240)
182240	0.717 (N=196,849)	0.710 (N=30,817)
183008	0.731 (N=224,745)	0.684 (N=2,921)
182244	0.712 (N=226,890)	0.782 (N=776)
182243	0.717 (N=223,354)	0.668 (N=4,312)
183006	0.719 (N=217,789)	0.660 (N=9,877)

Table 3: Model evaluation based on a spatial cross validation of 10x10 km blocks randomly assigned to five folds (in parenthesis the number of GPS locations included in each dataset).

Fold	Training AUC	Testing AUC
1	0.714 (N=188,664)	0.699 (N=39,002)
2	0.724 (N=196,080)	0.710 (N=31,586)
3	0.727 (N=142,952)	0.686 (N=84,714)
4	0.733 (N=189,389)	0.698 (N=38,277)
5	0.723 (N=193,579)	0.705 (N=34,087)

The main drivers of the flight altitude behaviour were terrain steepness, wind speed, land cover and geological substrates (permutation importance 36.9, 17.7, 10.3, and 8.4%, respectively) (Fig. 5). Flying below 200 m a.g.l. was more likely to occur over steeper slopes exposed to strong winds and dominated by rocks, scree and forest (Fig. 6).

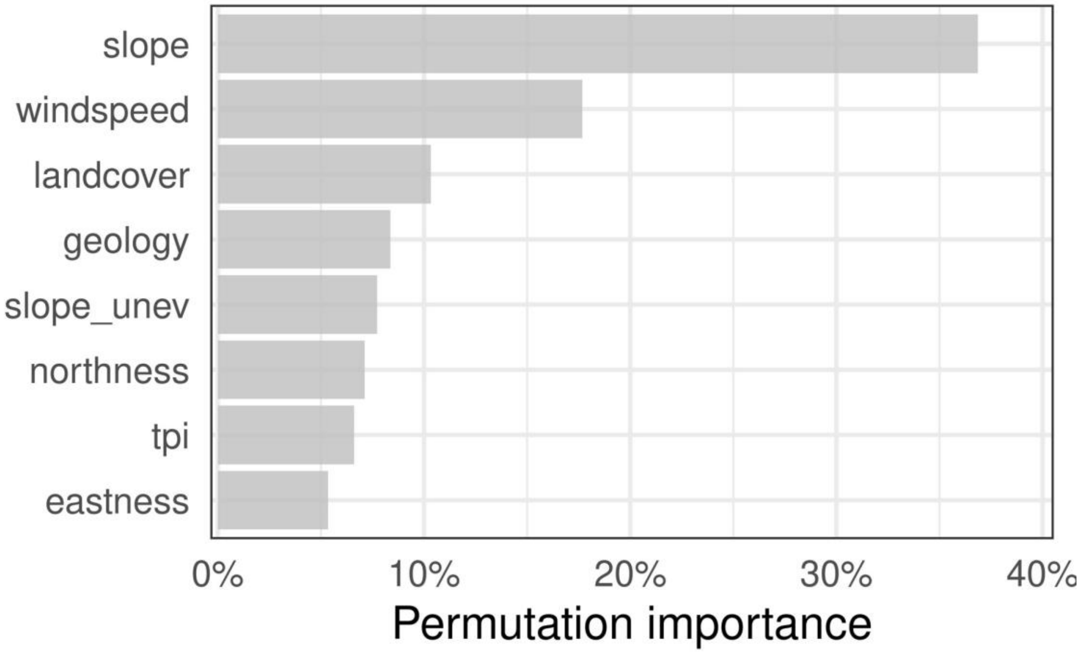


Figure 5: Variable importance given as permutation importance of the environmental variables used to model the probability of flying below the critical altitude of 200 m a.g.l. The permutation importance shows the percentage drop in training AUC when randomly permuting the values of the focal variable within its range.

Since the majority of the GPS locations used to train the model were collected within the Valais Alps (98%), the model was extrapolated only to this portion of the Swiss Alpine range (Fig. 7), in order to obtain reliable predictions. Finally, we performed a two-step process to convert the probability map to a multi-class high-risk conflict map and delineate the areas where it is more likely that eagles engage in risky, low-altitude flights (Fig. 8). In a first step, we selected two thresholds to convert the probability map to binary maps and delineate areas with different grades of potential conflicts. The first one was the threshold that led to a sensitivity of 95% (Vignali et al., 2022) and allowed to identify broad areas of conflicts These areas cover 67.5% of the Valais Alps and range from 378 to 4,610 m a.s.l. Considering that the population status of golden eagles in the Swiss Alps (Jenny, 2018) entails a much lower risk of demographic impacts than that of bearded vultures (Schaub et al., 2009), we used a second, less conservative threshold to highlight core areas for conservation. This second threshold was the Youden threshold, which maximises the sum of sensitivity and specificity and has already been used to identify areas of potential collision risk

for the Verreaux’s eagle (*Aquila verreauxii*) in South Africa (Murgatroyd et al., 2021). The areas delineated by using the Youden threshold cover 27.8% of the Valais Alps and range from 391 to 4,610 m a.s.l. In the second step, we aggregate the two binary maps into the multi-class high-risk conflict map by taking their sum.

The findings of this flight altitude model represent preliminary results not yet published and would require more specific analyses, especially regarding the actually available habitat for the species. Although the golden eagle in the Swiss Alps has currently reached its carrying capacity (Jenny, 2018), studying how the species selects the available habitat resources would help to prioritise the most suitable areas. This would allow to classify the areas overflown at low altitude in different classes of prioritisation and provide a complete and invaluable decision-making tool for wildlife managers and energy promoters.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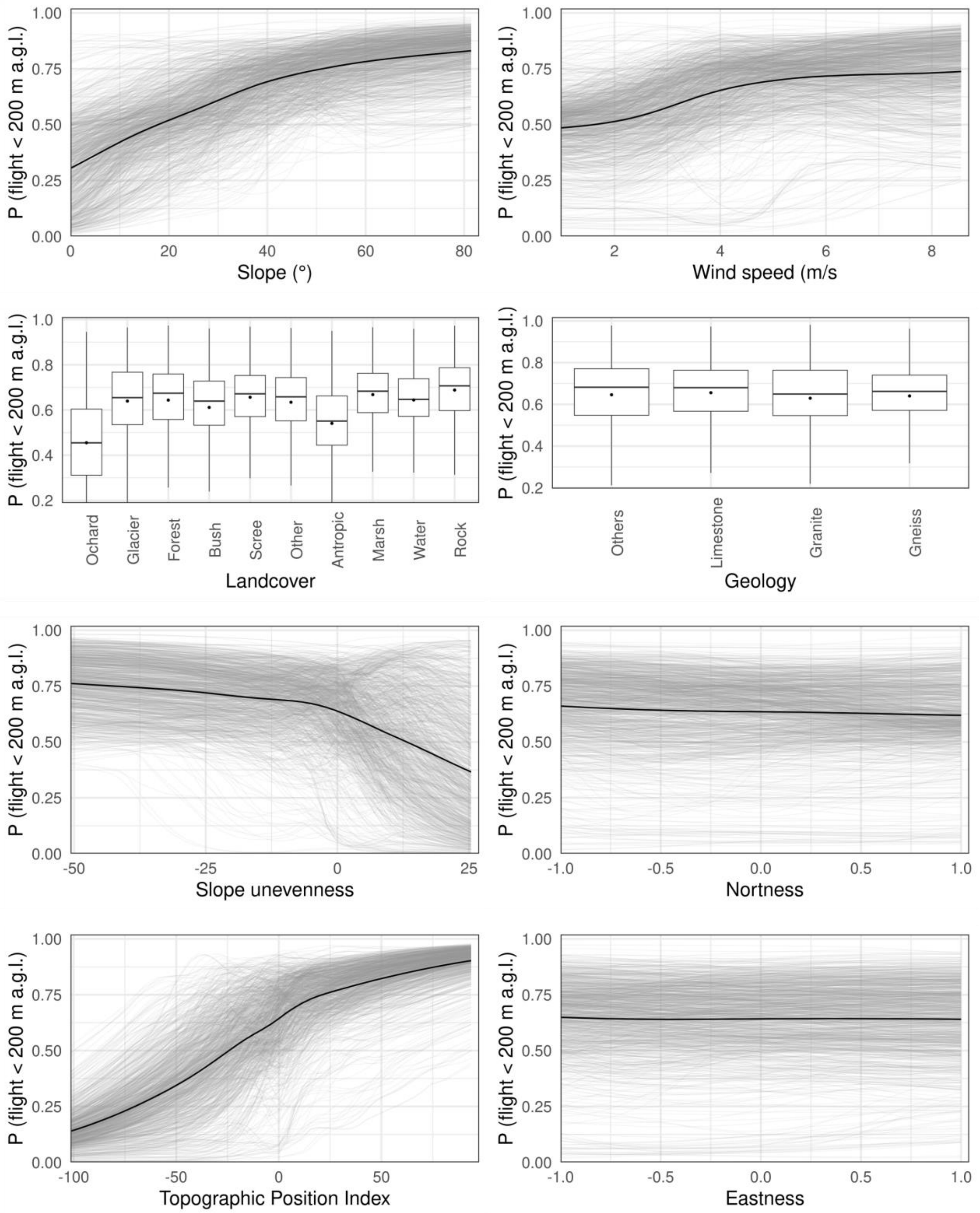

Figure 6: Effects of the environmental variables on the predicted probability of golden eagles flying below the critical altitude of 200 m a.g.l In grey are plotted 1,000 randomly sampled individual conditional expectation (ICE) curves (Goldstein et al., 2015) and in black the partial dependence (PD) curve (Friedman, 2001). For the categorical variables each boxplot represents the ICE values and the black dot the value of the PD (outliers are not shown).

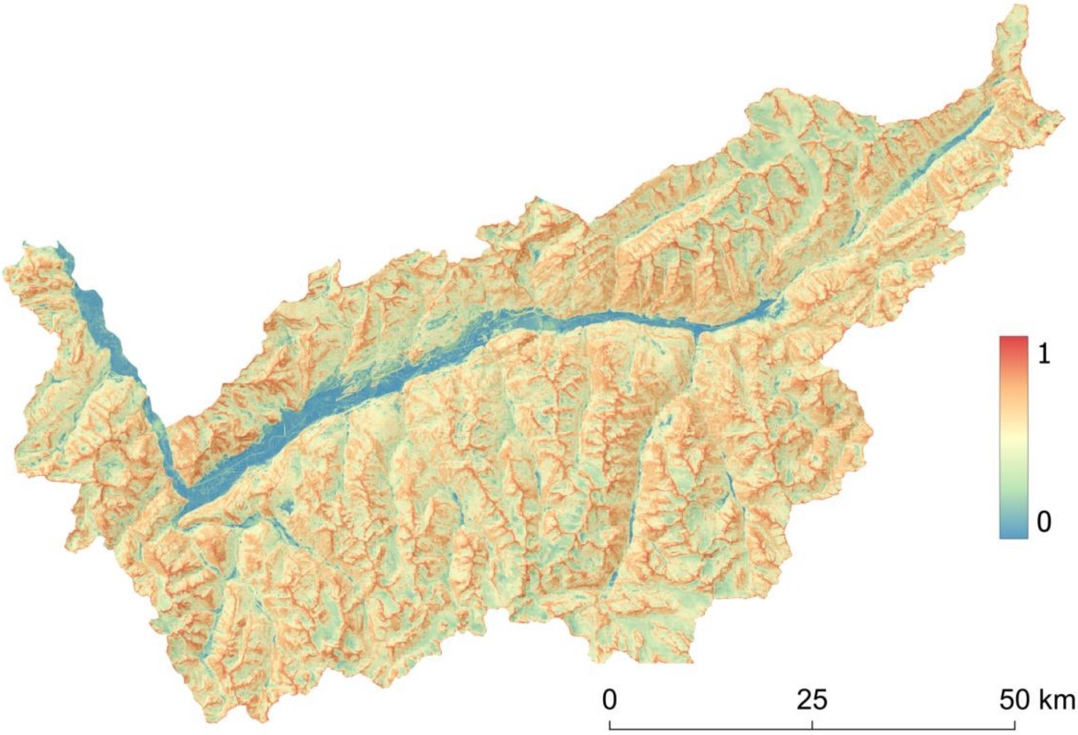

Figure 7: Predicted probability of a golden eagle flying below 200 m a.g.l. extrapolated to the Valais Alps. The probability is shown as gradient ranging from blue (zero probability) to red (high probability).

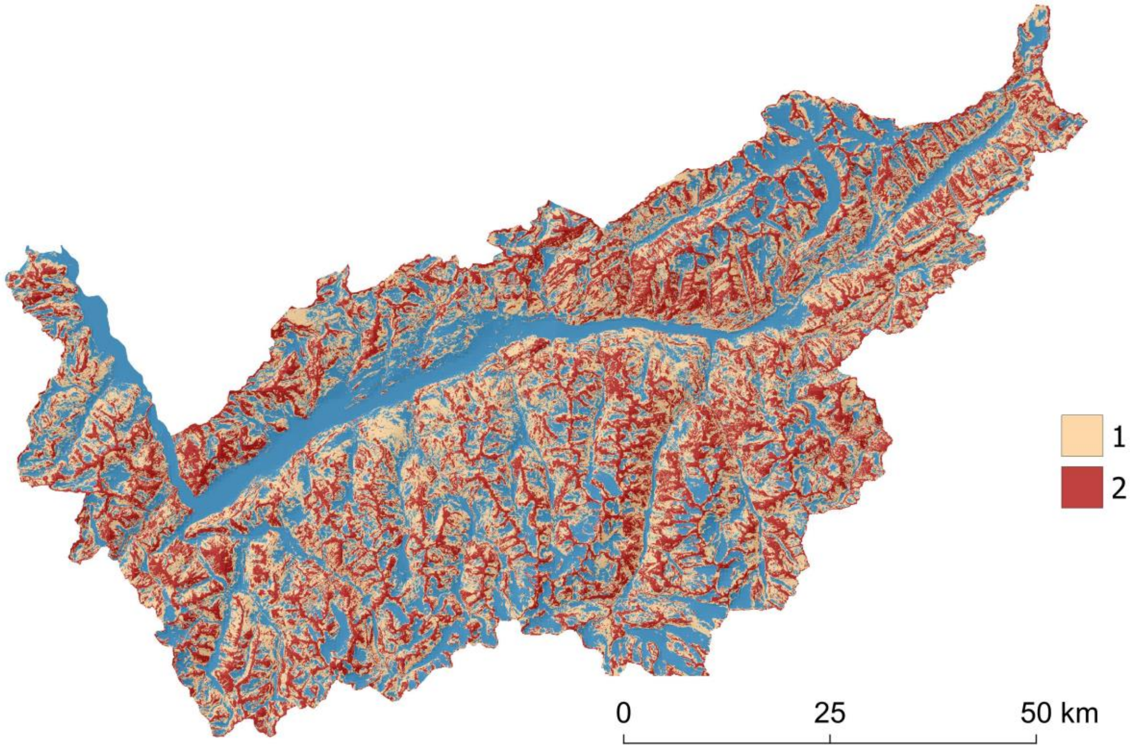

Figure 8: High-risk conflict map delineating the areas where golden eagles are likely to engage in risky, low-altitude flights; critical areas for eagle conservation are shown in red.


OUTLOOK AND FUTURE RESEARCH

Although we answered our initial research questions and developed the intended spatial planning tools for both species, with the experience gained from this project we identified a new key topic that will help to understand the way raptors interact with overhead obstacles. For this reason, we have decided to launch a second fundraising campaign with the goal of studying another critical aspect of the wind energy–raptors conflict, namely the flight avoidance behaviour. There is evidence that raptors often fail to detect obstacles while on the wing (Martin et al., 2012), especially during adverse weather conditions with scarce visibility, which led to visually mark cables and wind turbine blades (May et al., 2020) to enhance their detectability and reduce collision risk. However, little is known on the ability of raptors to memorise the presence of such obstacles and use this information to avoid dangerous areas. With this research we will dig into the species' behavioural response and adaptiveness to anthropogenic factors and provide unprecedented and original insights valuable for all stakeholders dealing with the wind energy- and general overhead infrastructure-wildlife conflict.

MAPS

All the maps produced for the bearded vulture are in the process to be archived in a public repository in collaboration with the Stiftung Pro Bartgeier. These maps are ready to be used by the end-users, i.e. policy makers, land planners, energy promoters and nature protection associations, and they are also attached as appendix or supplementary material to this final report.

The corresponding preliminary maps for the golden eagle are also attached as appendix. These maps are mostly indicative at this stage. They will be refined in the coming months to provide a more reliable zonation estimate.

Note that we have also built maps of occurrence for the red-billed chough (*Pyrrhocorax pyrrhocorax*) (Braunisch et al., 2021), a rare bird of Switzerland that may also be impacted by the wind energy development in the future. These maps are also attached to the report.

Finally, once the golden eagle conflict maps will be finalised, all the produced maps for these three key alpine species will be intersected to identify key areas of conservation interest in the context of airspace conflict with wind energy development.

APPENDICES

1. Maps

All appended maps are provided as both classical images with **.jpeg** extension and georeferenced raster file with **.tif** extension (EPSG 21781).

A. Bearded vulture

1. **bearded-vulture-probability.jpeg** and **.tif**: predicted join probability of bearded vulture occurrence and flying below 200 m a.g.l. (refer to figure 1 in this document and figure 3c of the published article related to chapter 3).
2. **bearded-vulture-high-risk-conflict-map.jpeg** and **.tif**: high-risk conflict map (refer to figure 2 in this document and figure 3f of the published article related to chapter 3).

B. Golden eagle

3. **golden-eagle-probability.jpeg** and **.tif**: predicted probability of flying below 200 m a.g.l. (refer to figure 7 of this report).
4. **golden-eagle-high-risk-conflict-map .jpeg** and **.tif**: areas where golden eagles are likely to engage in risky, low-altitude flights (refer to figure 8 of this report).

2. Documents

A. Bearded vulture

1. **phd-thesis-sergio-vignali.pdf**: document containing the doctoral dissertation of Sergio Vignali.
2. **chapter-1-phd-thesis.pdf**: published article related to chapter 1 of the PhD thesis of Sergio Vignali.
3. **chapter-2-phd-thesis.pdf**: published article related to chapter 2 of the PhD thesis of Sergio Vignali.
4. **chapter-3-phd-thesis.pdf**: published article related to chapter 3 of the PhD thesis of Sergio Vignali.

B. Golden eagle

5. **bachelor-thesis-anita-schmid.pdf**: Bachelor thesis of Anita Schmid.

SUPPLEMENTARY MATERIAL

1. **bearded-vulture-a.jpeg**: predicted probability of flying below 200 m a.g.l. (refer to figure 3a in Vignali et al. (2022)).
2. **bearded-vulture-b.jpeg**: predicted probability of bearded vulture occurrence (refer to figure 3b in Vignali et al. (2022)).
3. **bearded-vulture-d.jpeg**: binary map of flying below 200 m a.g.l. (refer to figure 3d in Vignali et al. (2022)).
4. **bearded-vulture-e.jpeg**: potential conflict map (refer to figure 3e in Vignali et al. (2022)).
5. **red-billed-chough.pdf**: published article on the red billed chough occurrence probability models.
6. **red-billed-chough.jpeg**: occurrence probability of red-billed chough in the Swiss Alps (this map synthesizes figure 3 of Braunisch et al. (2021)).

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