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Using Uncrewed Aircraft Systems to Create 3D Maps and Suitability Models of Golden Eagle Nesting Sites

By Emma Gregory

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Using Uncrewed Aircraft Systems to Create 3D Maps and Suitability Models of Golden Eagle Nesting Sites

Thesis Abstract-Idaho State University (2021)

The Morley Nelson Snake River Birds of Prey National Conservation Area (NCA) provides breeding sites for raptors in southwestern Idaho. Biologists have been mapping occupied Golden Eagle nest locations in the NCA since the 1960s, but the steep cliffs used by raptors as nesting sites are difficult to represent on traditional 2D maps. This study used uncrewed aircraft systems (UAS) equipped with multispectral sensors to collect imagery over Crater Rings National Natural Landmark within the NCA. Using different sensor systems, UAS platforms, and flight patterns, we investigated the most effective methods to collect imagery to create high quality 3D mapping products. Our findings show that using a façade style flight pattern paired with an obliquely faced red-green-blue camera provided digital maps with few holes and gaps over the cliff faces. We also developed a nest site suitability model using topographic parameters of slope, solar radiation, terrain ruggedness index, and height above the crater floor. The suitability model corresponded to current and historical nesting locations. These maps pinpoint areas important for nesting raptors and have the potential to investigate how changing climate and increasing invasive plants are influencing the availability of nest sites.

Key Words: Uncrewed Aircraft Systems, Golden Eagle, Suitability Model, 3D Mapping

Chapter 1. Introduction

1.1. Overview

Declines in bird species, including birds of prey, in the western United States are influenced by the combined effects of changes in land use, land cover, and climate, including warming throughout the year and decreasing precipitation (Betts et al., 2019). On the Snake River Plain in southwestern Idaho, specific threats to raptor populations include: deterioration and loss of shrub in the plant community, increasingly severe fires, expanding populations of invasive and noxious weeds, increased disturbance from motorized and non-motorized recreation, and plant community change caused by grazing livestock (BLM, 2008). Furthermore, with more mild winters on the Snake River Plain, birds of prey face the secondary challenge of increasing parasitism by insects on nestlings, raising levels of stress hormones and causing poor body condition and early fledging (Dudek, 2017).

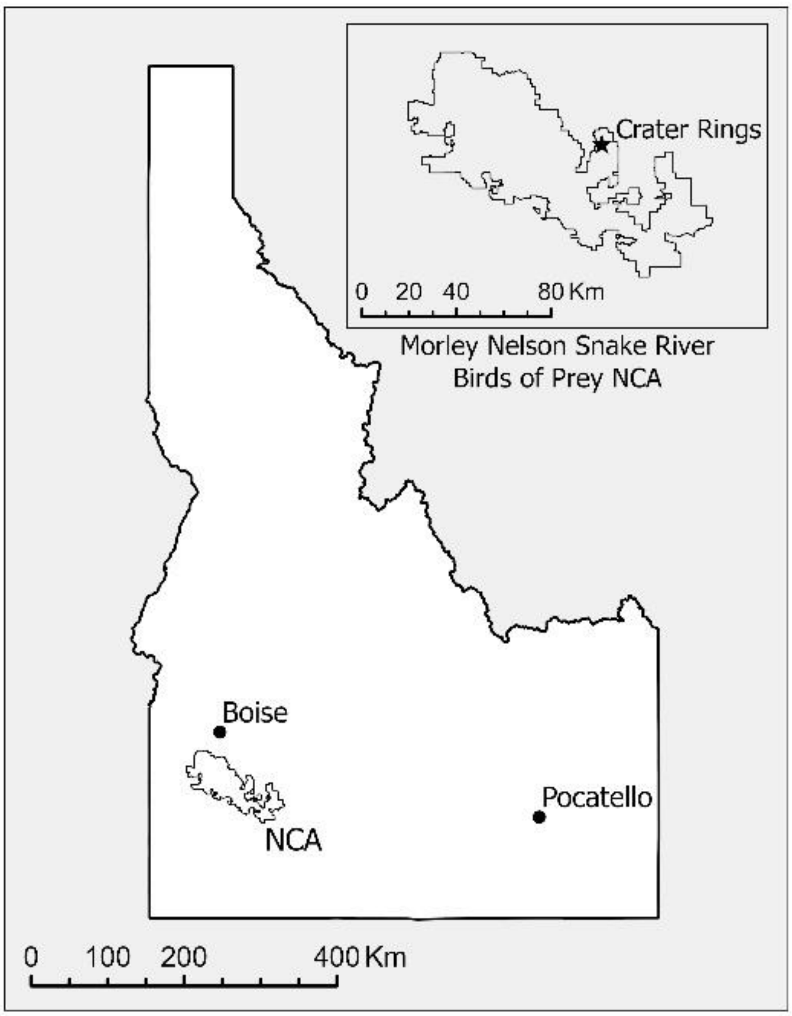

Figure 1. Morley Nelson Snake River Birds of Prey National Conservation Area and Crater Rings Natural National Monument in Southwestern Idaho.

To provide refuge for raptors in a changing environment, the 1,952.4 km^2 Morley Nelson Snake River Birds of Prey National Conservation Area (NCA) in southern Idaho was created in August of 1993 to protect the densest population of nesting raptors in the United States (Figure **1**) (Public-Law 103-64). The NCA is within a 30-minute drive of the greater Boise area, home to 749,202 people (U.S. Census Bureau, 2019), close to half of the population of Idaho. The Bureau of Land Management (BLM) manages the NCA, guided by the *Snake River Birds of Prey National Conservation Area Resource Management Plan and Record of Decision* (BLM, 2008). In addition to protecting nest sites for an array of bird of prey species, the NCA was designed based on radio-telemetry and prey studies to protect the food sources for raptors, namely Piute Ground Squirrels (*Urocitellus mollis*) and Black-tailed Jackrabbit (*Lepus californicus*) (Kochert and Pellant, 1986). The NCA is not only utilized by birds of prey and other wildlife, but also serves as a recreation area for hikers, cyclists, naturalists, shooters, and off-highway vehicles (OHV) (Spaul and Heath, 2016) and it is used as a training area for military operations (Belthoff and King, 2002), making it challenging for land managers and stakeholders to conserve the NCA for its varied utility. The NCA is bordered by both the Mountain Home Airforce Base and the Idaho National Guard Orchard Combat Training Center.

This pilot project focuses on the cliffs around the upper rims of Crater Rings National Natural Landmark (Figure 2) within the NCA and aims to create detailed 3D maps for long term modeling and visualizing nest locations. The steep, bare sides of the pit crater walls provide ideal nesting locations for Golden Eagles (*Aquila chrysaetos*), Prairie Falcons (*Falco mexicanus*), and Red-tailed Hawks (*Buteo jamaicensis*). As populations have increased in the nearby Boise metropolitan area (U.S. Census Bureau, 2019), the NCA and specifically Crater Rings Natural

National Landmark have faced mounting pressures from recreation such as shooting, hiking, biking, and OHV use, making monitoring birds of prey populations an important task to ensure their continued success.

To find occupied nest locations, technicians monitor bird activity and behavior in accessible territories across the NCA. Methods for recording occupied nest locations have

Figure 2. The basalt cliffs of the large crater at Crater Rings National Natural Monument

evolved through the years as technology has advanced. Historically, biologists recorded occupied nests by estimating and marking their locations on a paper map aided by aerial photographs. As handheld GPS became available in 2000, biologists working in the NCA transitioned to recording a global positioning system (GPS) point from directly above, below, or in the nest. In 2011 researchers began to refine nest points using Google Earth (GE) (Kochert, Personal Communication, September 7, 2021). Nest locations are typically rocky perches located on steep cliff faces that are out of reach of ground-based predators. Even with modern GPS technology, it is difficult to accurately map nest locations on 2D topographic maps due to the inherent overhead perspective where contour lines merge tightly together to represent steep slopes. Similarly, vertical to overhanging terrain blocks nest sites from view in imagery collected aerially or by satellite from directly above. In addition, the steep slopes of the basalt cliffs cast shadows that obscure the cliff faces in imagery. When overlaid on 3D terrain models, for example in GE, the imagery appears stretched and distorted, completely obscuring nesting locations and making it difficult for observers to accurately pinpoint nest locations. Uncrewed aircraft systems (UAS) allow researchers to resolve these issues by using different camera angles and flight patterns. Researchers using 3D models to monitor cliff changes have found that using UAS and flight patterns parallel to the cliff face have resulted in imagery that is not distorted when draped over terrain models (Dewez et al., 2016; Genchi et al., 2015). With UAS, researchers can collect imagery with oblique to 90° camera angles and scan vertical cliff faces with a series of overlapping lines. Using structure from motion (SFM) photogrammetry, the photos can be stitched together to generate a digital elevation model (DEM), image orthomosaic, and seamless 3D image of the cliff face, which, in the NCA, can be used to accurately represent nesting habitat. These products can be geo-referenced to facilitate accurate mapping. With a façade, or vertical face scanning approach, we can capture high quality, overlapping photos of cliffs using UAS which clearly captures the cliff faces as opposed to imagery collected by satellites or planes, where only the tops of the cliffs are clearly represented in the photos. These 3D products can also be used to refine historical nest locations that biologists have collected over the last six decades in the NCA, allowing for quicker and more accurate nest checks.

Using terrain data derived from SFM and known preferred habitat characteristics, researchers have created suitability models to determine which areas are most important to conserve and restore for given species. This method has been used with success to model suitable habitat for species including juvenile Tri-spine Horseshoe Crab (*Tachypleus tridentatus*) (Koyama et al., 2021), marine turtles (Kelly et al., 2017), and an endemic Hawaiian arthropod (*Nysius wekiuicola*) (Stephenson et al., 2017). Researchers have also used DEMs from SFM to study nest sites of White-rumped Sandpiper (*Calidris fuscicollis*) (Korne et al., 2020) and Gentoo Penguin (*Pygoscelis papua*) (McDowall and Lynch, 2017). The imagery collected by UAS as part of this project allows for the modelling of suitable nesting sites for Golden Eagles in the NCA.

1.2. Research Goals

The first research goal of this thesis was to create a suitability model to identify Golden Eagle nesting sites based on thermal and topographic characteristics. Although Golden Eagle populations in North America are largely stable (Millsap et al., 2013), small changes in adult survival can lead to population declines (Tack et al., 2017). We used UAS equipped with oblique RGB cameras and a MicaSense Altum multispectral and thermal sensor to take overlapping photos of the cliff faces. Using SFM and the photos, we generated digital elevation models, orthomosaics, and 3D models of the cliffs used for nesting. Using the DEM and orthomosaics of the study area, we created a suitability model based on previous research on nest site characteristics. We hypothesized that our model would identify areas with highly suitable nest sites on steep and rugged cliff faces that are protected from solar radiation and positioned high on the cliffs out of reach of ground-based predators.

The second research goal was to build interactive, 3D maps for long term monitoring and management using RGB imagery collected by UAS for mapping Golden Eagle nesting sites at Crater Rings National Natural Landmark. Traditional maps and GE use satellite imagery captured by a sensor pointing directly at the ground. We tried a series of sensor configurations and UAS platforms and found that by using obliquely to 90° pointing cameras and façade flight patterns, we accurately captured the cliff faces that Golden Eagles use to nest in the NCA. The resulting 3D maps showed nesting locations of raptors without the stretching, shadows, and holes that are unavoidable when capturing cliff imagery with a downward or nadir pointing sensor. In addition to representing the nest locations more accurately, the products created through structure from motion were high resolution (3-5 cm) and accessible to users through GE and online-compatible 3D viewers.

1.3. Broader Impacts

A suitability model for identifying optimal Golden Eagle nesting locations along the basalt cliff sides in the NCA will be helpful for long term monitoring and mapping of these sites in the Snake River canyon. Determining the areas preferred by nesting raptors ensures that biologists can focus their efforts, saving time and reducing disturbance to wildlife as they continue to search for new nesting locations within established territories. The suitability model will also help managers to identify the most important areas for Golden Eagle nesting in the NCA, allowing for the continued proactive protection of the NCA in accordance with the Resource Management Plan (BLM, 2008). In addition to benefiting biologists and land managers, as nest searching in the NCA continues and expands, the nest site suitability model may act as a guide for finding new nest sites, identifying sites that may be sensitive to a warming climate or sites where nesting is not possible due to the wind-driven accumulation of invasive plants.

3D maps that accurately display nest locations are beneficial to land managers, planners, and biologists for making management decisions to protect Golden Eagle nest sites and continuing monitoring efforts in the NCA. The current maps include nest locations that are sometimes inaccurate due to changes in methods of plotting nest locations on maps, the transition from 2D topographic maps to platforms such as GE, and the steep or overhanging nature of the cliffs which makes imagery appear stretched, dark, and shadowed or smeared. This can confuse observers in the field when pinpointing nest locations and could lead to errors in data collection, such as duplicated nest points or incorrect assessment of nest occupancy if the historical nest location is not accurate or obvious. UAS based 3D maps captured with façade scanning are more efficient for displaying existing and historical nests than traditional methods, save time and effort, and result in a better and more user-friendly products that managers and researchers can display on easily accessible online platforms or in the form of a printable map or image that researchers can carry into the field. Additionally, maps that accurately represent the cliff faces are unique and not available through any other source. Researchers will be able to use the 3D maps in the field as nest monitoring efforts at historical nests continue and when recording newly discovered nesting locations.

It is important to monitor and study natural areas that are still supporting vigorous ecosystems, such as the NCA, in a climate that is changing due to human activities (Chaplin et al., 2000). As researchers observe changes in nest site selection and nesting success amid climatic shifts and the accompanying threats of changing plant communities and increasing parasitism, representative maps will allow for easy tracking of nest sites in a 3D format and will help them understand how species use topography to adjust. Variations in nesting success and the characteristics of successful nests may shed light on how managers can work to preserve the Golden Eagle nesting habitat that will offer the greatest success to raptors in the NCA in the future.

Chapter 2. Literature Review

2.1. Birds of Prey in the Morley Nelson Snake River Birds of Prey National Conservation Area

The Morley Nelson Snake River Birds of Prey National Conservation Area (NCA) covers 195,325 ha of southern Idaho (Stuber, 2015). The NCA was created in 1993 through an act of congress to protect essential breeding and wintering habitat for raptors (Sharpe and van Horne, 1998; Stuber, 2015). The NCA lies in the southwest corner of Idaho along the Snake River where summers are hot and dry, and winters are moderate. Between 1991 and 2020, the NCA received an average winter (December-February) precipitation of 6.07 cm and had an average winter temperature of 1.94 ˚C. Average summer (June-August) precipitation was 2.54 cm and average summer temperature was 24.5˚ C (NOAA, 2020). The plant community historically has been dominated by shrub such as sagebrush (*Artemisia* spp.), rabbitbrush (*Ericameria nauseosa*), bitterbrush (*Purshia tridentata*), winterfat (*Krascheninnikovia lanata*), shadescale (*Atriplex confertifolia*), and native grasses, but in recent years increasingly large populations of cheatgrass (*Bromus tectorum*), tumble mustard (*Sisymbrium altissimum*), and other invasive plants (Kochert and Pellant, 1986) have taken root in the region. Tumble mustard, in particular, has been driven by wind into large accumulations along the cliff ledges and walls of the NCA.

The NCA holds the densest breeding population of non-colonial nesting raptors in the world, with Prairie Falcon (*Falco mexicanus*), Golden Eagle (*Aquila chrysaetos*), Barn Owl (*Tyto alba*), Burrowing Owl (*Athene cunicularia*), Long-eared Owl (*Asio otus*), Short-eared Owl (*Asio flammeus*), Red-tailed Hawk (*Buteo jamaicensis*), Ferruginous Hawk (*Buteo regalis*), Great Horned Owl (*Bubo virginianus*), American Kestrel (*Falco sparverius*), Northern Harrier (*Circus cyaneus*), Swainson's Hawk (*Buteo swainsoni*), Turkey Vulture (*Cathartes aura*), Osprey (*Pandion haliaetus*), and Western Screech-owl (*Megascops kennicottii*). All use the area for rearing chicks (Kochert and Pellant, 1986). Furthermore, the NCA provides important wintering grounds for Rough-legged Hawk (*Buteo lagopus*) and Bald Eagle (*Haliaeetus leucocephalus*) (Kochert and Pellant, 1986). Steep cliff sides for nesting and perching, abundant prey species of ground squirrels and Black-tailed Jackrabbit, and the lack of heavy winter snowpack makes the NCA an ideal location for nesting and wintering, particularly for Golden Eagles and Prairie Falcons.

Monitoring raptor species allows biologists to study how the actions of humans and the effects of a changing climate affect their populations in the western United States. The topography and large size of the NCA makes surveying for and monitoring raptor nests challenging. Technicians carry out monitoring efforts by observing nests from the tops and bases of the cliffs using spotting scopes and binoculars along with historical nest points viewed in Google Earth (GE) and photographs of the cliff faces with nest areas highlighted. Highly accurate 3D maps created from UAS imagery would benefit researchers working in the NCA by making finding, documenting, and monitoring nest locations for continued and new activity more streamlined and accurate. The currently available maps through GE and other satellite-based and manned aerial imagery that are created with a downward pointing sensor do not accurately capture basalt cliffs in the NCA. When this imagery is viewed in 3D, the cliffs appear stretched, distorted, and contain holes and shadows where overhanging areas are not fully captured. Furthermore, nest site suitability models along the cliff sides in the NCA would allow land managers and researchers searching to focus their efforts on locations most likely utilized by raptors and monitor how nest location preferences are evolving with a changing climate.

Previously, there have been several studies within the NCA of landscape changes and threats to raptor populations. Changes in the plant community of the NCA due to invasive plants and repeated fires are likely to have broad effects on the ecology of the area as non-native vegetation increasingly dominates areas once covered with brush and native grasses (Shinneman et al., 2015). Population densities of Piute Ground Squirrels, an important food source for raptors living in the NCA, are greater in areas of natural vegetation than areas dominated by invasive plants (Tinkle, 2016). Although broad landscape and prey population changes are occurring, increasing numbers of raptors are utilizing the NCA for wintering grounds as the wintering ranges shift northward due to the effects of climate change (Paprocki et al., 2015). In addition to the challenges posed by changes in habitat and climate, the damaging effects of pesticide use (Stuber et al., 2018), recreation (Opdahl, 2018; Spaul and Heath, 2016; Steenhof et al., 2014), and parasites (Dudek, 2017; Dudek et al., 2018) on nesting raptors have been documented within the bounds of the NCA.

2.2. Threats to Birds of Prey

North American bird populations have been in decline across many taxonomic groups in recent decades as human dominated landscapes have grown (Leu et al., 2008; Sauer and Link, 2011). This increase in anthropogenically-altered ecosystems has reinforced the need for areas, such as the NCA, that provide stable and high-quality habitat for the diverse raptor population of southern Idaho. However, even within the sheltered bounds of the NCA, there are mounting threats facing birds of prey.

The NCA lies about 64 kilometers south of Boise, where the population has increased by an estimated 9.3% in the last decade alone (U.S. Census Bureau, 2019). With a growing population, the number of people seeking outdoor recreation opportunities including shooting, hiking, biking, and OHV use in the NCA and other natural landscapes surrounding Boise has similarly increased, causing stress to raptors and negatively affecting territory occupancy and nesting (Spaul and Heath, 2016). In addition to increased recreational pressures, climate change has led to greater parasitic stresses on raptors in the NCA as the historical ranges of parasites have changed with increasing temperatures (Sánchez-Guillén et al., 2016).

2.2.1. Changes in Plant Community

The compounding effects of fire, noxious and invasive weeds, and grazing are leading to a concerning loss of shrub and broad changes in the plant community of the NCA (BLM, 2008). This loss of sagebrush and shrub further contributes to the abundance of exotic plants, including cheatgrass, due to the increased resources available in the absence of shrub (Prevéy et al., 2010). While plant community changes do not affect raptors directly, plant communities dominated by exotic plants lead to less stable populations of prey, namely Black-tailed Jackrabbit and Piute Ground Squirrel, which support the diverse raptor populations of the NCA (Steenhof and Kochert, 1988; Yensen et al., 1992).

Fire, invasive plants, and grazing are interconnected in the ways that they influence plant communities and in turn raptor success in the NCA. For four to six years after a burn, fire influences breeding success of Golden Eagles residing in territories where the pair did not have room to expand into neighboring empty territories (Kochert et al., 1999). Changes in yearly wildfire patterns have been exacerbated by the expansion of cheatgrass and other exotic annuals, with longer fire seasons and more frequent fires spreading from areas dominated by exotic plants with built up fuels into native vegetation (Shaw et al., 1999). Grazing also contributes to the spread of invasive plants such as cheatgrass, with a greater abundance of cheatgrass located closer to grazing allotments and more sparse populations farther from grazing allotments (Raymondi, 2017). The effects of fire, invasive plants, grazing and loss of shrub exacerbate the degradation of sagebrush steppe, negatively affecting prey species that raptors in the NCA depend on.

2.2.2. Parasites

Historically found in Mexico and the Southwestern United States, the Mexican Chicken Bug (*Haemotosiphon inodorus*) is a blood sucking ectoparasite that has been documented to affect nine species of raptor as well as domesticated birds (Grubb et al., 1986). The ranges of many insects have expanded northward as anthropogenic climate change has taken effect (Sánchez-Guillén et al., 2016) and, similarly, Mexican Chicken Bugs have expanded into the NCA from their historical range. The increase in winter temperatures and decrease in snowpack across the west (Abatzoglou and Kolden, 2011) have likely aided in the expansion of the Mexican Chicken Bugs' range into the NCA.

In 1992, Mexican Chicken Bugs were determined to be a source of mortality in Prairie Falcon nestlings reared in the NCA (McFadzen and Marzluff, 1996) and they are now being studied as a source of mortality and increased stress in Golden Eagle nestlings (Dudek, 2017). Research into the factors that increase the likelihood of Mexican Chicken Bug infestation in the nests of Golden Eagles has shown that variables such as southern aspect, warmer nest temperature, more frequent use between breeding seasons, and short distance to other nests increases the likelihood of infestation while the use of aromatic plants as an insect repellent decreases infestation in Golden Eagle nests (Dudek, 2017).

2.2.3. Recreation

Aside from providing invaluable nesting habitat for birds of prey, the NCA also provides space for recreational activity from nearby population centers in the Treasure Valley, such as Boise and its surrounding cities. Popular activities in the area include hiking, off-highway vehicle (OHV) use, mountain biking, and shooting. Recreation opportunities are increasing in popularity as research shows the benefits to human health of spending time enjoying the outdoors (Opdahl, 2018). Each of these activities creates disturbance to nearby nesting birds through noise created by the activity or by humans being present in the territory being utilized to rear chicks (Opdahl, 2018). A study of OHV use in southern Idaho found that areas with heavy OHV use produced fewer Golden Eagle young than nests in areas not impacted by OHV (Steenhof et al., 2014). An accurate, user friendly, accessible three-dimensional map of occupied raptor nests would be useful to biologists and managers of the NCA in preventing or minimizing disturbance during sensitive times in the breeding season by providing the information necessary to restrict access to areas with high nest density.

2.3. UAS, Remote Sensing, and Bird Monitoring

Wildlife biology and habitat assessment has historically been performed by placing researchers directly into the system of interest or, more recently, through the use of imagery captured by satellites and small aircraft (Anderson and Gaston, 2013). Problems exist with both the traditional and modern methods of conducting habitat research. By studying systems through ground based, in-person research, there can be disturbances to wildlife and delicate ecosystems (Tin et al., 2009). While the use of satellites mitigates the invasiveness of ground-based observations, the spatial and temporal resolution provided is not ideal for many research questions (Olsoy et al., 2018). Uncrewed aircraft systems (UAS) are changing the ways that we study habitat through their ability to provide high quality imagery with a greater temporal and spatial resolution than is available through traditional, satellite based sensors (Anderson and Gaston, 2013). In addition to improving the spatial and temporal resolution of imagery, UAS makes it possible to scan more complex landscapes such as steep and overhanging cliffs (Dewez et al., 2016; Genchi et al., 2015).

Researchers have used UAS and fixed-wing manned aircraft to monitor breeding birds across different landscapes. Minimizing disturbance to breeding birds is a concern when conducting monitoring and it has been found to be possible with UAS if carefully planned with the correct platforms for data collection (Borrelle and Fletcher, 2017). UAS were successfully used to monitor occupied Steller’s Sea Eagle (*Haliaeetus pelagicus*) nests that were previously only accessible through climbing, and the UAS method was found to be more ethical and efficient when compared to climbing nest trees (Potapov et al., 2013). The adult Steller’s Sea Eagles associated with the monitored nests did not behave aggressively towards the UAS, however, the UAS were approached by interested but non-aggressive Eurasian Hobby (*Falco subbuteo*) on two occasions (Potapov et al., 2013). Common Gulls (*Larus canus*) and Black-headed Gulls (*Chroicocephalus ridibundus*) have been studied within breeding colonies using imagery collected by UAS classified to count breeding pairs (Grenzdörffer, 2013; Sardà-Palomera et al., 2012). When used to monitor Common Tern (*Sterna hirundo*) colonies, UAS based counts of nests accurately accounted for 93%-96% of nests that were found with ground-based counts. The UAS counts were much less disruptive to breeding and rearing activities (Chabot et al., 2015). A survey of four Alaskan species of seabird nesting in cliffs found no impact of UAS flights on breeding success and as well as increased success of detecting camouflaged chicks when compared to ground-based surveys (Brisson-Curadeau et al., 2017). Moreover, planes with thermal imaging cameras have been used to efficiently and accurately count Columbian Sharp-tailed Grouse (*Tympanuchus phasianellus columbianus*) on leks (Gillette et al., 2015).

2.4. 3D Mapping in Ecology

Because animals utilize the vertical dimension of the landscape in addition to the horizontal, 3D mapping in ecology can help researchers gain insights into important aspects of habitat. 3D data can provide information about available cover, structural complexity, vegetation density, and landscape ruggedness. Traditionally, 3D mapping for ecological studies has used light detection and ranging (lidar). Lidar has been used to study habitat structure for a variety of taxa including invertebrates (Müller and Brandl, 2009; Vierling et al., 2011; Work et al., 2011), aquatic species (Kuffner et al., 2007), non-flying vertebrates (Coops et al., 2010; Sillero and Gonçalves-Seco, 2014), and flying vertebrates. Researchers have emphasized 3D mapping of aquatic species and flying vertebrate habitats because of these species' flexible use of three-dimensional space and the importance of vertical habitat characteristics. With the advancement of UAS, lidar data can be collected more affordably than by low-flying aircraft. However, it still requires the use of specialized and expensive sensors (D'Urban Jackson et al., 2020).

Instead of using lidar, researchers can capture much of the same structural data using a structure from motion (SFM) approach with affordable, consumer- grade cameras on foot or from a UAS. A comparison of shrub biomass density calculated from lidar and SFM showed that the resulting biomass models had similar precision and the SFM model had the added benefit of containing multispectral data, which can be used in classifications and to make multispectral orthomosaics and 3D models (Alonzo et al., 2020). In more densely vegetated landscapes, SFM has been an effective technique for mapping forest canopies but has not provided sufficient coverage of the underlying topography (Wallace et al., 2016). SFM has been used to successfully create 3D maps of marine habitats (Bryson et al., 2017; Burns et al., 2015; Kalacska et al., 2018), tidal wetlands (Kalacska et al., 2017), forests (Frey et al., 2018), rivers (Dietrich, 2016; Marteau et al., 2017), and cliffs (Ružić et al., 2014). In a direct comparison of SFM and LIDAR used to map the coastal cliffs of Fort Funston, California, an error of 0.30 m was present between the two methods, showcasing the accuracy that can be obtained with SFM methods (Warrick et al., 2017). When using SFM to map a landslide in steep terrain in Tasmania, the processing for a single acquisition date over a one-hectare area took 5.9 hours (Lucieer et al., 2014). Ultimately, SFM is as effective at modeling complex landscapes as traditional lidar and has the added benefits of collection with an affordable, consumer-grade camera, multispectral imagery, and it produces not only a DEM but also orthomosaics and 3D models.

A potential benefit of using 3D mapping in ecology is increased accuracy of locations plotted on a 3D map. Because habitat does not exist in two dimensions, using 3D mapping allows researchers to pinpoint the exact locations of features where there is variation on the z axis as well as the x and y. In addition to providing increased accuracy, creating 3D maps preserves landscapes in a digital form that will remain unchanged. This unchanged, digital copy is ideal for comparison if there are major changes to the landscape that affords continued study of the habitat without physically being present. The 3D models of landscapes are beneficial to researchers who are studying ecosystems or species that are particularly sensitive to human disturbance and to researchers whose field areas are difficult to access or far away. In addition to preventing unnecessary disturbance, 3D models have the potential to create opportunities for researchers to safely study sites in rough terrain.

2.5. UAS Image Processing

Structure from motion (SFM) is a method (Figure 3) for creating a three-dimensional scene from a series of overlapping images, such as those created by a moving sensor (Marteau et al., 2017). Images for use with SFM can be obtained with any digital camera from the ground, UAS, or low flying aircraft, making this method cost effective and practical for a wide array of applications (Javernick et al., 2014). The best method for image collection is dependent on the topography and size of the area of study (Westoby et al., 2012). After obtaining imagery for the area of interest, identifying features, or keypoints, must be detected (Smith et al., 2015). This process can be automated by using one of several keypoint detectors such as SIFT (Scale-Invariant Feature Transform), SURF (Speeded Up Robust Features), or ORB (Oriented FAST (Features from

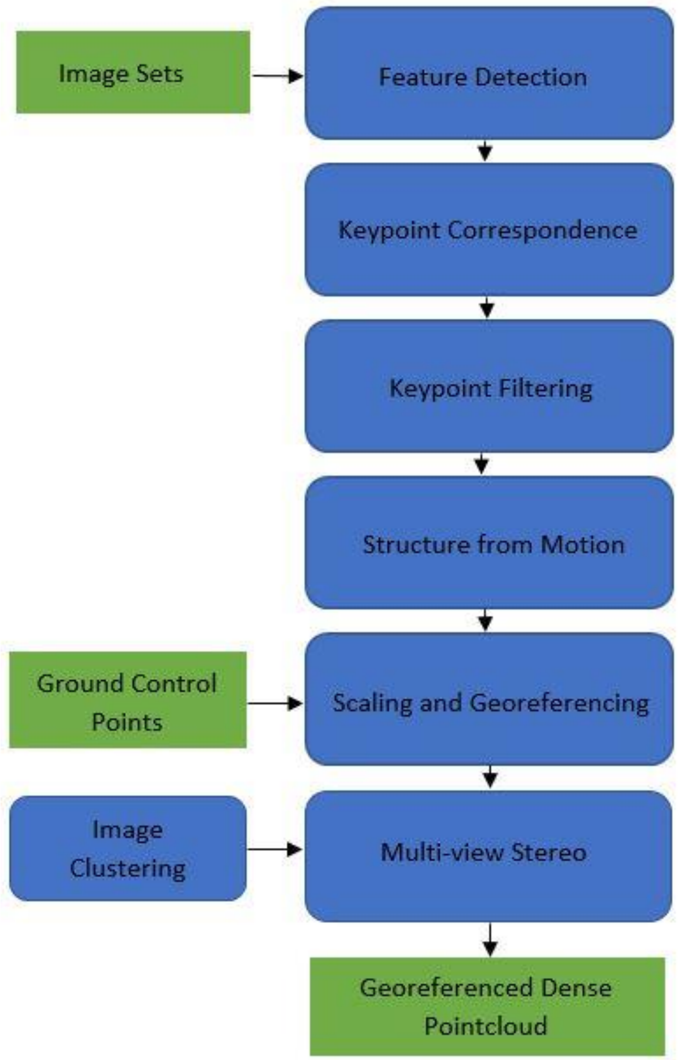

Figure 3. Typical SFM workflow adapted from Carrivick, Smith, and Quincey (2016). The inputs and outputs are shown in green.

Accelerated Segment Test) and Rotated BRIEF (Binary Robust Independent Elementary Features)) (Rublee et al., 2011). After identifying keypoints between the images, Bundler (a sparse bundle adjustment system), can determine the position and orientation of the camera and generate a low-density point cloud (Westoby et al., 2012). The Clustering View for Multi-view Stereo (CMVS) and the Patch-based Multi-view Stereo (PMVS2) software packages can pre-process the resulting camera positions from Bundler and generate a more dense point cloud (Westoby et al., 2012). The final steps in creating the 3D image using SFM include manually identifying at least three ground control points in the image for georeferencing and generating a Digital Elevation Model (DEM) from the point cloud in ArcGIS Pro or other software (Smith et al., 2015). These processes can alternatively be done using the Agisoft Metashape software package (Li et al., 2016).

2.6. Habitat Suitability Mapping

Habitat suitability maps consist of pixels that have been assigned values that represent how ideal each cell is for a particular species based on sets of habitat variables (Hirzel et al., 2006). In studying raptors, researchers have effectively used aerial photographs from manned aircraft and imagery from satellites to create suitability models specifically for nesting habitat in different landscapes for species including Common Buzzard (*Buteo buteo*) (Austin et al., 1996), New Zealand Falcon (*Falco novaeseelandiae*) (Mathieu et al., 2006), Eleonora's Falcon (*Falco eleonorae*) (Urios and Martínez-Abraín, 2006), Powerful Owl (*Ninox strenua*) (Isaac et al., 2008), Gyrfalcon (*Falco rusticolus*), and Golden Eagles (*Aquila chrysaetos*) on the Iberian Peninsula (López-López et al., 2007). These studies found metrics measured from remote sensing techniques such as slope, terrain ruggedness, elevation, aspect, surrounding vegetation, and prey availability are useful criteria for mapping likely nest sites for raptors. Combining the chosen layers, they are able to highlight the most suitable nesting sites within a study area. In recent years, imagery collected by UAS combined with SFM photogrammetry was used to create habitat suitability models for a wide variety of organisms including Showy Stickseed (*Hackelia venusta*) (Foster, 2021), Tri-spine Horseshoe Crab (*Tachypleus tridentatus*) (Koyama et al., 2021), and Gentoo Penguin (*Pygoscelis papua*) (McDowall and Lynch, 2017). The suitability models resulting from UAS imagery are highly detailed and allow for the study of fine scale features.

2.7. Ethics and Sensitivity

The ethical concerns of this project fall into two main categories: stress and disturbance to birds of prey by UAS during data collection and misuse of the resulting maps from the research. Raptors are most sensitive to disturbance from anthropogenic sources between the months of March and September when breeding and nesting are occurring (Suter and Joness, 1981), so minimizing disturbance to those residing in the NCA was a priority moving forward. This is the first bird of prey study conducted with UAS in the NCA, however, researchers have effectively monitored birds elsewhere using UAS. A study of wetland birds in Europe found that by flying no closer than 4 m from resting or feeding birds and by using a horizontal as opposed to vertical approach, the birds were unperturbed by UAS flights. (Vas et al., 2015). While using UAS to monitor Steller's Sea Eagles nests, researchers found that adults would fly to a safe distance while UAS were being operated but would return upon the conclusion of the flights (Potapov et al., 2013). A study of bird and drone interactions in Australia similarly found no negative interactions between raptors and drones (Lyons et al., 2018).

The use of UAS is an exciting new frontier in avian research but researchers should exercise an abundance of caution and have proper training and to prevent accidents when using these methods. In 2021, irresponsible hobby UAS pilots have caused several accidents resulting in bird deaths and abandonment of nests including a UAS crash into an Elegant Tern colony leading to the abandonment of 1,500 nests and 2,000 eggs (Thompson, 2021) and a crash into a Bald Eagle nest leading to its abandonment (Geha, 2021). With proper training, respect for wildlife, and an aim towards conservation and stewardship, researchers can avoid these types of accidents by following regulations.

Three dimensional maps that show the locations of raptor nests could potentially be abused by members of the public if they were made widely available. Unethical bird watchers and photographers could all be sources of harm to breeding Golden Eagles in the NCA by harassing birds during the breeding season. Protecting the nest locations of these birds is of utmost importance as this project continues and the resulting maps will be for management and research purposes only. This pilot project is in partnership with the Bureau of Land Management (BLM) and the data and resulting maps are for the agency and not released to the public.

Chapter 3. Nest Site Suitability Modeling for Golden Eagles within the Morley Nelson Snake River Birds of Prey National Conservation Area

3.1. Introduction

Nest site characteristics are the set of factors that determine if an area is advantageous for rearing chicks and are dependent on the needs of a particular species. For example, researchers studying raptor breeding ecology in the Morley Nelson Snake River Birds of Prey National Conservation Area (NCA) in southwest Idaho have investigated these characteristics and how they influence nest site selection (Beecham and Kochert, 1975; Belthoff and King, 2002; Kochert and Steenhof, 2012; Marks, 1986; Marzluff et al., 1997b; Ogden and Hornocker, 1977). Using field-based measurements and observations, researchers have determined that aspect (MacLaren et al., 1988; Runde and Anderson, 1986), height (MacLaren et al., 1988; Marks, 1986; Runde and Anderson, 1986), exposure to solar radiation (Beecham and Kochert, 1975), distance from other nests (Beecham and Kochert, 1975), slope (MacLaren et al., 1988), and proximity to native vegetation (Marzluff et al., 1997b) are factors that can influence raptor nest site selection. Previous field-based studies of raptor breeding ecology have shown that the mean aspect for Golden Eagle, Ferruginous Hawk (*Buteo regalis*), and Prairie Falcon (*Falco mexicanus*) nest sites in the western United States is 300˚, with an aspect of 278˚ specifically for Golden Eagles (MacLaren et al., 1988). Cliffs used by Golden Eagles for nesting have an average slope of 23.1˚ (MacLaren et al., 1988). The location of nest sites in the NCA is influenced by the composition of the surrounding plant community, with Golden Eagles and Prairie Falcons both preferring nesting near native plant communities with Big Sagebrush (*Artemisia tridentata*), Winterfat (*Krascheninnikovia lanata*), and rabbitbrush (*Chrysothamnus sp.*) (Marzluff et al., 1997a, 1997b). Raptor preferences for particular plant communities likely relates to the association of healthy populations of prey species such as Black-tailed Jackrabbit (*Lepus californicus*) and Piute Ground Squirrel (*Urocitellus mollis*) with native shrubs (Knick and Dyer, 1997; Van Horne et al., 1997). Although close proximity to other raptor nests can lead to greater exposure to hematophagous parasites that are a major source of mortality for young raptors (Dudek, 2017), the deciding factor for Golden Eagle nest proximity to other nests seems to be related site availability, with low quality cliffs having less dense nesting populations than high quality cliffs (Beecham and Kochert, 1975). The average distance between Golden Eagle nests in the NCA is 3.5 km (Kochert and Steenhof, 2012) while the distance between Prairie Falcon nests in the NCA has been documented as low as 0.94 km (Ogden and Hornocker, 1977). Exposure to thermal radiation is another important consideration for raptors when selecting a nest site. Between the ages of 3 and 6 weeks, young Golden Eagles have been found to have high mortality associated with heat stress (Beecham and Kochert, 1975), showing the importance of finding a nest site with protection from solar radiation.

Breeding raptor populations in the NCA are facing increased pressures from a variety of anthropogenic forces. Rapid urban population growth in the Greater Boise Metropolitan Area (U.S. Census Bureau, 2019) has led to increasing recreation disturbance from hiking, shooting, and motorized use. Additionally, land cover change due to climate, wildfires and the expansion of invasive plants such as cheatgrass (*Bromus tectorum*) and tumble mustard (*Sisymbrium altissimum*) (Stuber, 2015) are reducing habitat for prey species (Tinkle, 2016). To monitor the impact of these pressures in the NCA there is a need to continue and expand raptor population monitoring. One solution is to leverage predictive mapping to identify potential nesting locations allowing managers and researchers to efficiently allocate resources for expanding monitoring programs across larger areas. Pinpointing areas most important to raptor nesting will allow for continued protection and rehabilitation of these spaces. Further, predictive mapping can inform changes in nesting patterns and behaviors and provide a guide to future limitations in nest site selection due to changing environmental conditions.

To accurately create nesting site maps, aerial photographs from manned aircraft and imagery from satellites have been previously established as effective tools for identifying preferred nesting locations for raptors in different landscapes including Common Buzzard (*Buteo buteo*) (Austin et al., 1996), New Zealand Falcon (*Falco novaeseelandiae*) (Mathieu et al., 2006), Eleonora's Falcon (*Falco eleonorae*) (Urios and Martínez-Abraín, 2006), Powerful Owl (*Ninox strenua*) (Isaac et al., 2008), Gyrfalcon (*Falco rusticolus*), and Golden Eagles (*Aquila chrysaetos*) on the Iberian Peninsula (López-López et al., 2007). Like field-based observations, these studies have found metrics measured using remote sensing techniques such as slope, terrain ruggedness, elevation, aspect, surrounding vegetation, and prey availability are useful criteria for mapping nest sites for raptors. However, capturing aerial photographs from manned aircraft is expensive and satellite imagery does not have high enough resolution to map nest sites at a local scale. Futhermore, capturing nesting locations on a steep or overhanging cliff using a nadir sensor on a plane or satellite results in imagery with voids and stretching. Uncrewed aircraft systems (UAS) equipped with multispectral sensors or consumer grade cameras are an efficient and affordable alternative for capturing imagery of a study area (Westoby et al., 2012) at a higher resolution than is possible by plane or satellite (Anderson and Gaston, 2013). Images collected with overlap can be used in structure from motion photogrammetry (SFM) to create digital elevation models (DEM), multispectral maps, point clouds, and 3D models of a study area (Fonstad et al., 2013). These products have been used to study nest site preferences for bird species including colonial nesting herons (Bakó et al., 2020), Gentoo Penguin (*Pygoscelis papua*) (McDowall and Lynch, 2017), White-rumped Sandpiper (*Calidris fuscicollis*) (Korne et al., 2020), and Burrowing Parrot (*Cyanoliseus patagonus*) (Genchi et al., 2015).

In order to create predictive maps of Golden Eagle nesting sites in the NCA, we followed the following four steps adapted from (Mathieu et al., 2006):

1. Choosing important nesting site characteristics from published literature (rugosity, thermal radiation, slope, and elevation)
2. Collection of UAS data to examine the chosen nest site characteristics
3. Creation of predictive maps based on nest site characteristics, data from the UAS, and SFM photogrammetry
4. Evaluation of the predictive maps using nest site observations collected by BSU biologists

In this pilot study, we sought to create a model for predictive mapping using data layers derived from a digital elevation model (DEM) with the future goal of testing the model against a larger dataset across 50 km of Golden Eagle nesting sites along the Snake River Canyon. By using predictive mapping to find areas that are most likely to support nesting Golden Eagles, researchers in the NCA can streamline survey efforts, thereby allowing monitoring efforts to cover more of the NCA.

3.2. Methods

3.2.1. Study Site

The study area for this research is the large or east crater in Crater Rings National Natural Landmark which lies within the Morley Nelson Snake River Birds of Prey National Conservation Area (NCA) in Southwestern Idaho (Figure 4 and Figure 5). The 195,325 ha Morley Nelson Snake River Birds of Prey National Conservation Area (NCA) in southern Idaho was created in August of 1993 to protect the densest population of nesting raptors in the United States (Public Law 103-64) and is managed by the Bureau of Land Management (BLM) (BLM, 2008). The NCA lies along the Snake River and experiences hot, dry summers and moderate winters. The plant community consists of Sagebrush (*Artemisia* spp.), Rabbitbrush (*Ericameria nauseosa*), Bitterbrush (*Purshia tridentata*), Winterfat (*Krascheninnikovia lanata*), Shadescale (*Atriplex confertifolia*), native grasses, and increasingly Cheatgrass (*Bromus tectorum*) and other invasive plants (Kochert and Pellant, 1986). In addition to providing habitat for large populations of raptors, the NCA is home to abundant prey species including Piute Ground Squirrel (*Urocitellus mollis*) and

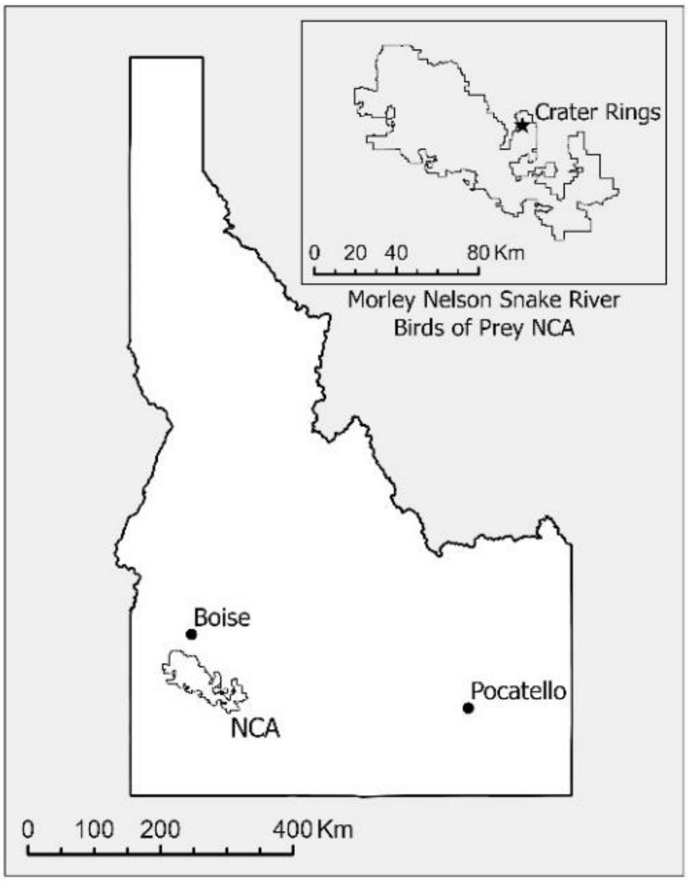

Figure 4. Morley Nelson Snake River Birds of Prey National Conservation Area and Crater Rings National Natural Landmark.

Black-tailed Jackrabbit (Kochert and Pellant, 1986). The twin craters and surrounding areas provide excellent nesting locations for Golden Eagles and Prairie Falcons. We chose the large crater as the pilot study area for this project because of the ease of access and eight historical Golden Eagle nesting sites within the crater and one occupied nest site at the time of the flights.

Figure 5. Crater Rings National Natural Landmark, Morley Nelson Snake River Birds of Prey National Conservation Area. Image source: Esri, USDA FSA.

3.2.2. Nest Site Locations

In the early spring of 2020, biologists from Boise State University (BSU) surveyed the large crater for raptors and observed one pair of Golden Eagles, three pairs of Prairie Falcons, and one pair of Common Ravens nesting along the walls of the crater. They recorded nest locations with a handheld, consumer grade GPS from directly above, below, or in nest and then refined this point using Google Earth (Kochert, Personal Communication, September 7, 2021).

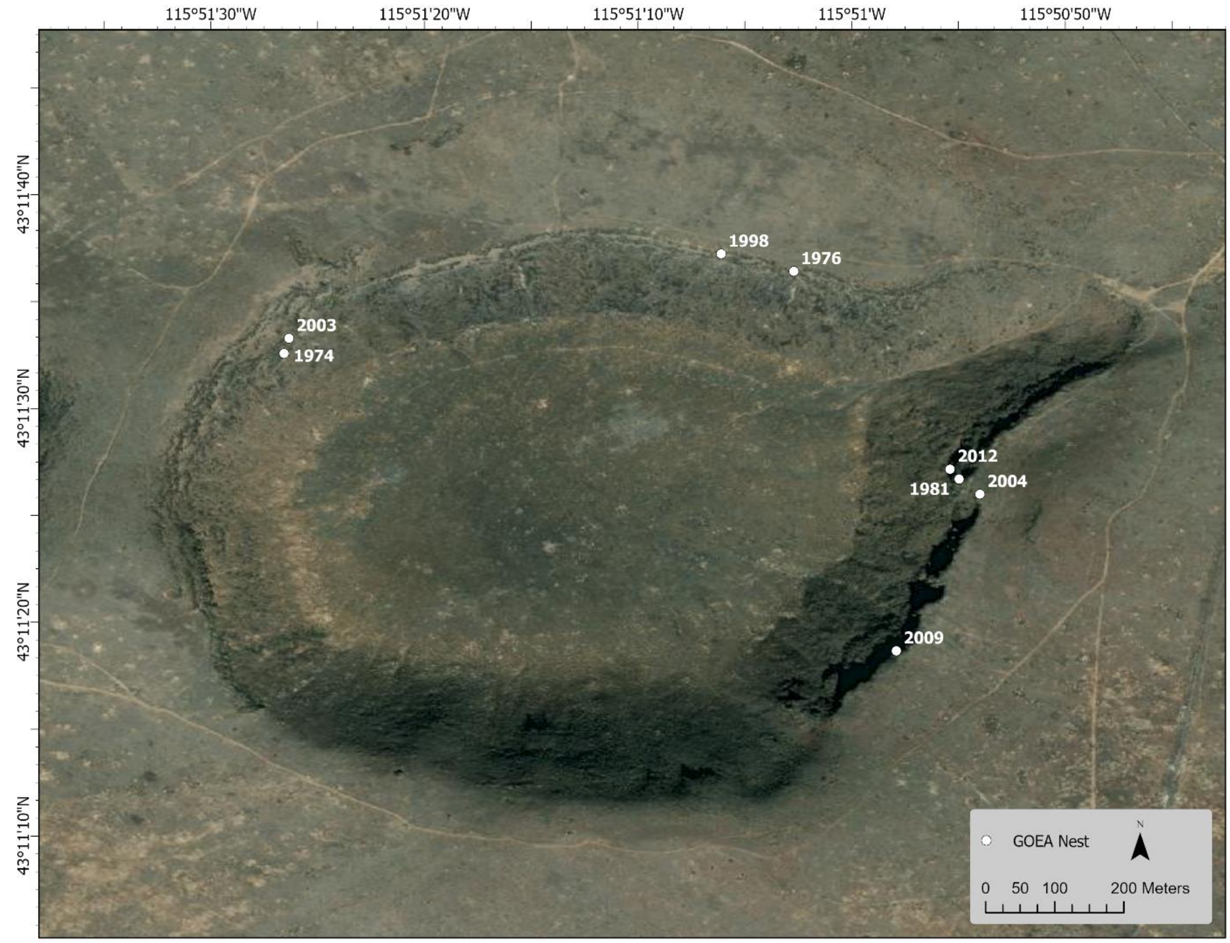

Figure 6. Historical Golden Eagle (GOEA) nest locations at the Large Crater. Image source: Esri, USDA FSA.

As well as the nests occupied in 2020, we considered historical Golden Eagle nest locations in the crater dating back to 1974 (Figure 6). The historical nest locations were documented using aerial imagery from a plane and 7.5-minute quadrangles from the United States Geologic Survey. After originally being documented when first discovered, the nest locations were marked with a GPS in the early 2000s (Kochert, Personal Communication, September 7, 2021).

3.2.3. Nest Site Suitability Characteristics

Using previous research on the nesting preferences of Golden Eagles along with nesting data from the pilot site study area, we created nest site suitability maps that characterize raptor nest site choice using slope, terrain ruggedness index, height above ground level, and solar radiation. Other models predicting Golden Eagle nesting habitat on the Iberian Peninsula using satellite imagery found that Golden Eagles preferentially nested in areas with rugged terrain, which in both the NCA and on the Iberian Peninsula, represents the areas with high quality cliffs (López-López et al., 2007). Other cliff nesting raptors have been found to prefer steep cliff sides for nesting where they will be protected from ground-based predators (Booms et al., 2010; Mathieu et al., 2006). Because of the similarity of nesting habitat between Golden Eagles and other cliff nesting birds, we included slope as a predictive characteristic in our final model. Similarly, elevation is an important nest characteristic for protecting nestlings from predators that could potentially reach them from the ground and Golden Eagles nesting in trees have shown preference for higher nesting locations (MacLaren et al., 1988). High nestling mortality has been associated with high temperatures in nests, especially prior to nestlings developing the ability to thermoregulate (Beecham and Kochert, 1975). Because of nestlings' susceptibility to high temperatures, we chose solar radiation over the breeding period as the final consideration in the nest site suitability model. Aside from the importance of these four factors to cliff nesting raptor breeding ecology, each of these layers can be derived from a digital elevation layer (DEM), which can be easily created from RGB imagery with a consumer grade camera using SFM. We used imagery collected with the MicaSense Altum sensor to validate the solar radiation layer derived from the DEM and to investigate the effect invasive plants and climate change is having on Golden Eagle nest sites in the NCA.

3.2.4. UAS Data Collection

3.2.4.1. Ground Control

Prior to the UAS flight survey at the study area, we placed ground control points (GCP) throughout the crater. To prevent distress to the nesting raptors in accordance with the Migratory Bird Treaty Act of 1918 (16 U.S.C. §§703-712) and the Bald and Golden Eagle Protection Act (16 U.S.C. §§668-668D), we created a 400 km buffer around the Golden Eagle

Figure 7. Crater Rings National Natural Landmark with nest locations, corresponding buffer zones to prevent disturbance, and ground control points. Image source: Esri, USDA FSA.

nest and a 100 km buffer around all other nests where we did not place ground control. In total, we placed 57 at the large crater at random outside of the buffer zones created to protect nests from disturbance (Figure **7**). After placing the GCP, we collected coordinates at each point using a Topcon HiPer II GPS system, which collects points with an accuracy of less than 5 cm.

3.2.4.2. Platform and Sensors

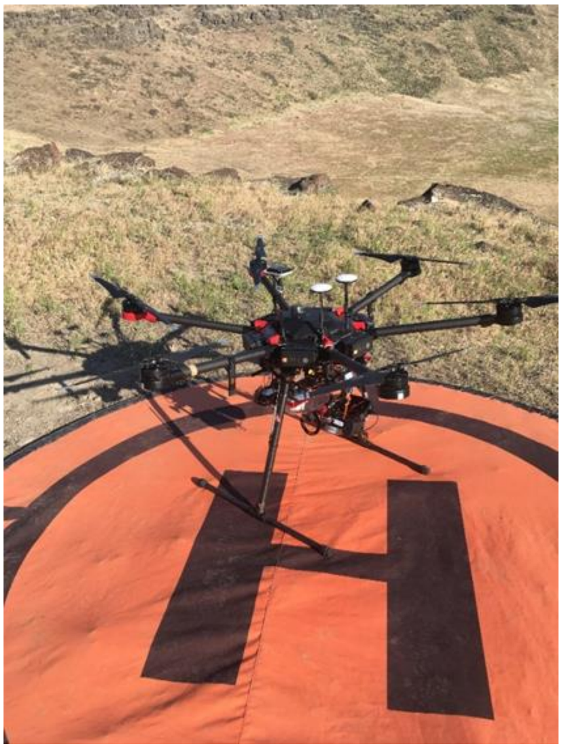

Figure 8. Matrice 600 Pro with Sony Alpha 6000s and MicaSense Altum.

We conducted our UAS survey using a Matrice 600 Pro (SZ DJI Technology Co., Ltd) (Figure **8**) equipped with two sensor systems. One system consisted of a MicaSense Altum camera that collected imagery in six bands (Table 1) and includes an onboard GPS. The thermal and multispectral sensors are radiometrically calibrated and attached to the UAS with a DJI SkyPort. We also used a digital mirrorless camera (Sony Alpha a6000 camera with an E16 mm lens) collecting Red-Green-Blue imagery. We attached the camera facing directly down from the UAS, or nadir. The settings we used for the Sony Alpha a6000 camera were focal point of infinity, f-stop of four, shutter speed of 1/800, and ISO of 100.

Table 1. MicaSense Altum spectral bands

Band	Wavelength
Blue	475 nm center, 32 nm bandwidth
Green	560 nm center, 27 nm bandwidth
Red	668 nm center, 16 nm bandwidth
Red Edge	717 nm center, 12 nm bandwidth
Near Infrared	842 nm center, 57 nm bandwidth
Thermal	8-14 µm

3.2.4.3. Mission Planning and Flights

We obtained permission from the BLM for conducting UAS flights in the NCA and fulfilled the necessary Institutional Animal Care and Use Committee (IACUC) protocol prior to data collection at Crater Rings. We conducted UAS flights on May 28th, 2020, May 29th, 2020, and June 5th, 2021 at the large crater. We collected imagery at 100 meters AGL with both the MicaSense Altum and a nadir Sony Alphas a6000 taking photos at two second intervals. To ensure 75% sidelap in the photos, the side distance was set at 22 m and the flight speed was set at 5 m/s. We based the flight speed and side distance from the MicaSense Altum thermal band, which has a narrower field of view than the Sony Alpha a6000 cameras. We conducted flight planning using Universal Ground Control Software (UgCS) (Figure 9). In UGCS, we used the terrain following option to plan the flights to maintain 100 m distance from the surface. For the terrain source, UgCS uses the Shuttle Radar Topography Mission (SRTM) DEM that has a resolution of one arc second (approximately 30 m).

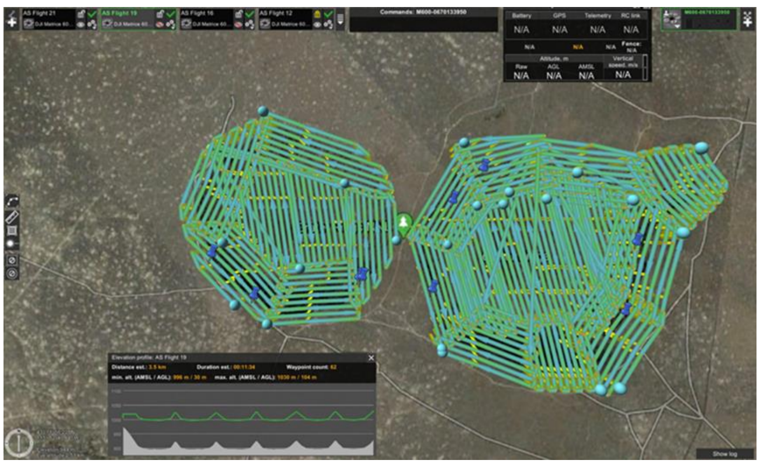

Figure 9. Flight paths for the 100 m AGL flights over both craters.

As UAS image collection operations were underway, four of the BSU biologists were present to observe and record behavioral data on the nesting raptors at the crater. They watched for signs of stress such as adults leaving the nests for abnormally long periods of time, excessive calling, and attempts to interfere with the UAS to prevent conflict between the nesting raptors and the data collection, as well as providing insight on the reactions of breeding raptors in the NCA to the presence of UAS.

3.2.5. Predictive Mapping

3.2.5.1. Image Processing

To adjust for differing light conditions over two days of flights, we adjusted the exposure of the photos from the Sony Alpha a6000 in Adobe Lightroom. No pre-processing was necessary for the imagery collected by the MicaSense Altum sensor due to calibration of the imagery using a target with known reflectance prior to the flights. We used Agisoft Metashape Pro version 1.7.5 to create thermal and multispectral maps, a digital elevation model (DEM), dense point clouds, and a 3D model of the large crater. For imagery collected with both the Sony Alpha a6000 camera and the MicaSense Altum, we used ground control points collected in the crater to georeference the imagery for further analysis. In Agisoft Metashape Pro, we set the alignment at high accuracy, and we built the dense point cloud with the quality set at high. To create the DEM, we used the dense point cloud as the source data.

3.2.5.2. Data Layers

To model nest site selection, we used the DEM generated from the Sony Alpha 6000 cameras and Esri ArcGIS Pro version 2.8.3 to generate data derivatives that included: height

Table 2. Golden Eagle nest site selection data layers.

Dataset	**Description**
Terrain Ruggedness Index	Change in elevation between a raster cell and its neighbors
Solar Radiation	Amount of solar radiation received by a raster cell over the nesting period
Slope	Slope gradient (degrees)
Height from Crater Floor	Height above cliff base

from crater floor, slope, solar radiation, and terrain ruggedness index (TRI) (Table 2). The original resolution of the DEM was 13 cm, but we resampled it to an accuracy of one meter to decrease processing time and filter out noise in the data. We calculated the slope of every cell in the large crater in degrees by taking the maximum change in elevation divided by the distance between each cell and its eight neighbors. We converted the elevation data from meters above sea level to meters above ground level where the lowest point of the base of the crater was set as 0 m. We created the TRI raster using the 1 m resolution DEM and calculating the elevation difference between each cell in the DEM and its eight surrounding neighbors. All eight elevation differences are then squared, then averaged, then the square root is taken, resulting in a unitless TRI measurement for each cell (Riley et al., 1999). We calculated incoming solar radiation for the entire crater from March 17 until June 29th. These dates were chosen based on the earliest recorded hatch dates for Golden Eagles chicks in the NCA until six weeks after the latest recorded hatch date, knowing that Golden Eagle chicks are particularly susceptible to heat stress in the first six weeks of life (Beecham and Kochert, 1975). We calculated the solar radiation using methods developed by Rich et al., 1994 using a day interval of one and an hour interval of 0.5.

3.2.5.3. Suitability Modelling

To create the suitability model, we followed the workflow outlined in Figure **10** Using the previously established nest site preferences of Golden Eagles and the layers of data derived

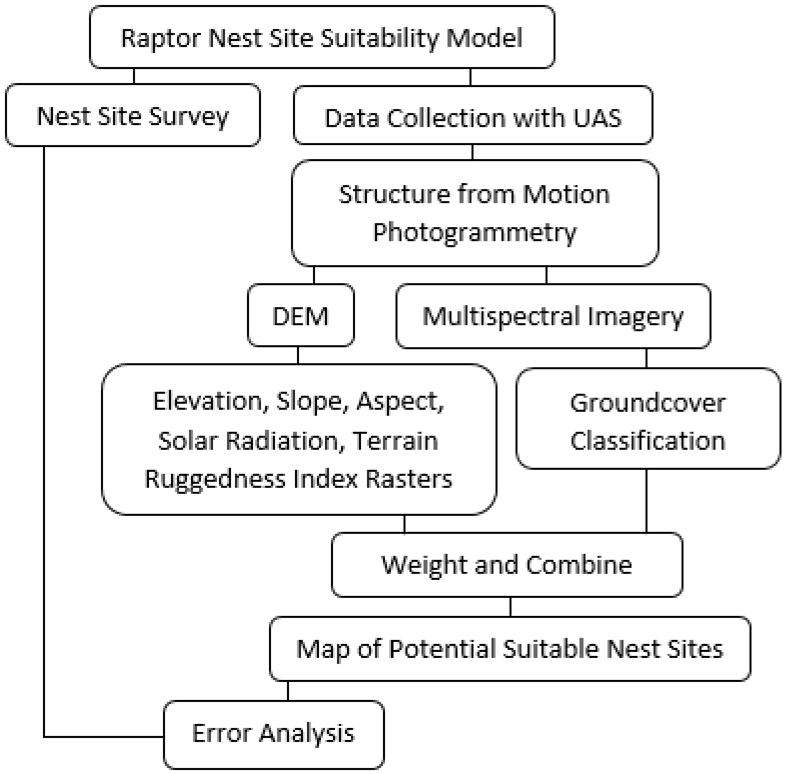

Figure 10. Workflow for creating suitability model using imagery collected by UAS.

Table 3. Data layers included in the habitat suitability model and the transformation curve applied to each.

Data Layer	**Function**	**Midpoint**	**Point Spread**	**Lower Threshold**	**Upper Threshold**	**Weight**
Terrain Ruggedness Index	Large	10.01	1	0.00086	20.02	30%
Solar Radiation (WH/m^2)	Small	287,065.13	5	71,872.88	400,000	30%
Slope (˚)	Large	40.42	5	45	80.82	30%
Elevation AGL (m)	Large	30 m	1	10 m	116.46 m	10%

from the UAS imagery (Table 3), we transformed each layer to a 0-10 suitability scale, with high values assigned to pixels most suitable for nesting. For the solar radiation layer, we gave highest preference to regions with the lowest solar radiation values, where topography protects the nestlings from heat stress. For the TRI, slope, and elevation layers, we assigned preference to large values. There are other metrics that can be manipulated when transforming each data layer to a suitability scale to manipulate the suitability values that each cell in the raster receives. For the TRI layer, we left the midpoint as the center point in the data and did not set an upper or lower threshold. We did not set a lower threshold for the solar radiation layer, but we did set an upper threshold of 400,000 WH/m^2. Cells receiving more solar radiation than this during the nesting period are too exposed, leading to heat stress in nestlings in the time before they are adequately able to regulate their own body temperature. For the slope layer, we set a lower threshold of 45 degrees to help pinpoint cliffs and not more gently sloping hillsides where predators would have easy access to nests. To transform the elevation layer, we set a lower threshold of 10 m because it was unlikely that raptors would be found nesting below this value. We also changed the midpoint to 30 m but did not set an upper threshold. The transformation curve metrics for each layer was manipulated according to previous research on nest site preferences and the tool documentation (ESRI, 2021).

After transforming each layer to a common suitability scale, we weighted the layers to represent their importance in the final model for predicting good raptor nesting locations. The TRI, solar radiation, and slope layers were each assigned a weight of 30% as they seemed to be equally good indicators of highly suitable nesting sites. We assigned the elevation layer a weight of 10% because there are large areas of the imagery that do have a high elevation but are clearly not suitable for nesting. Elevation is an important aspect of nest site suitability but is less informative than the other three layers when looking for areas that are likely to hold nesting raptors. With all layers transformed to a common suitability scale and weighted, we combined them into a single suitability model. With the suitability map of nesting sites created, we overlaid documented nest site locations to assess if the model was a good predictor of nest site suitability in the NCA. For each documented Golden Eagle nest, we created a 10 m buffer around the nest to represent the error of the hand-held GPS unit used to collect the point. We then reported the pixel with the highest suitability value within the 10 m buffer.

3.2.6. Evaluation of Predictive Maps

3.2.6.1. Sensitivity Analysis

To gauge the sensitivity of the suitability model to each data layer included, we manipulated the weight of each layer and looked for changes in the final resulting model. We chose to increase the weight of each layer by 9% one at a time, while also decreasing the weight of each other layer by 3% to maintain a model where the layer weights totaled 100%. We assessed changes in the final model by visually comparing the original model to each of the sensitivity analysis models and by counting all cells in the original model and the sensitivity analysis models that had a suitability of greater than seven and all cells that had a suitability of greater than eight.

3.2.6.2. Classification and Thermal Mapping

We performed Random forest classifications (Breiman, 2001) on the Micasense Altum orthomosaic images for the craters using eight bands: red, green, blue, NIR, red-edge, thermal, normalized difference vegetation index (NDVI), and revised modified soil-adjusted vegetation index (MSAVI2). To assess cover type, we chose to classify the imagery into four classes: basalt, tumble mustard, living vegetation, and dried vegetation. We created training datasets for each individual flight to account for differences in light conditions at the time we collected the imagery. The number of training samples for each class ranged between 4 and 12 to create classes with approximately even number of pixels. The maximum number of trees was set to 50, maximum tree depth was set to 30, and the maximum number of samples per class was 1000. To assess the accuracy of the resulting classifications, we created separate testing datasets for each flight and then generated confusion matrixes for the classifications on each section of the imagery.

The thermal imagery we collected using the MicaSense Altum was recorded in centi-Kelvin. In Agisoft Metashape Pro, we converted the raw centi-Kelvin values to Celsius by dividing the original value by 100 and then subtracting 273.15. This provided us with an easily understood snapshot image of the ground temperature at the time we collected the imagery. We then visually compared this imagery to the solar radiation layer generated from the DEM to determine if the solar radiation layer was a reliable proxy for looking at cliff temperatures during the breeding season.

3.3. Results

3.3.1. Derived Data Products and Transformations

To create the DEM, we used 13,800 photos which covered 152 ha. The ground resolution of the resulting DEM was 3.31 cm/pixel and the reprojection error was 0.437 pixels. The TRI, slope, height, and solar radiation layers (Figure 11) were scaled using the parameters shown in Table 3, which translated to the scaling curves, resulting in the transformed layers that show suitability on a 0-10 scale (Figure 12 and Figure 13). Independently, the terrain ruggedness, slope, and solar radiation layers were effective at highlighting the cliffs surrounding the craters that Golden Eagles use for nesting. The transformed height layer, however, looked drastically different from the other three with all areas above 10 m shown as being highly suitable. Some areas designated as suitable by the height layer were high on the grassy and gently sloping hills surrounding the cliffs where nesting was unlikely to occur. We chose not to set an upper limit to the elevation layer so that the nest site suitability model would be easy to use across the NCA where cliff heights vary.

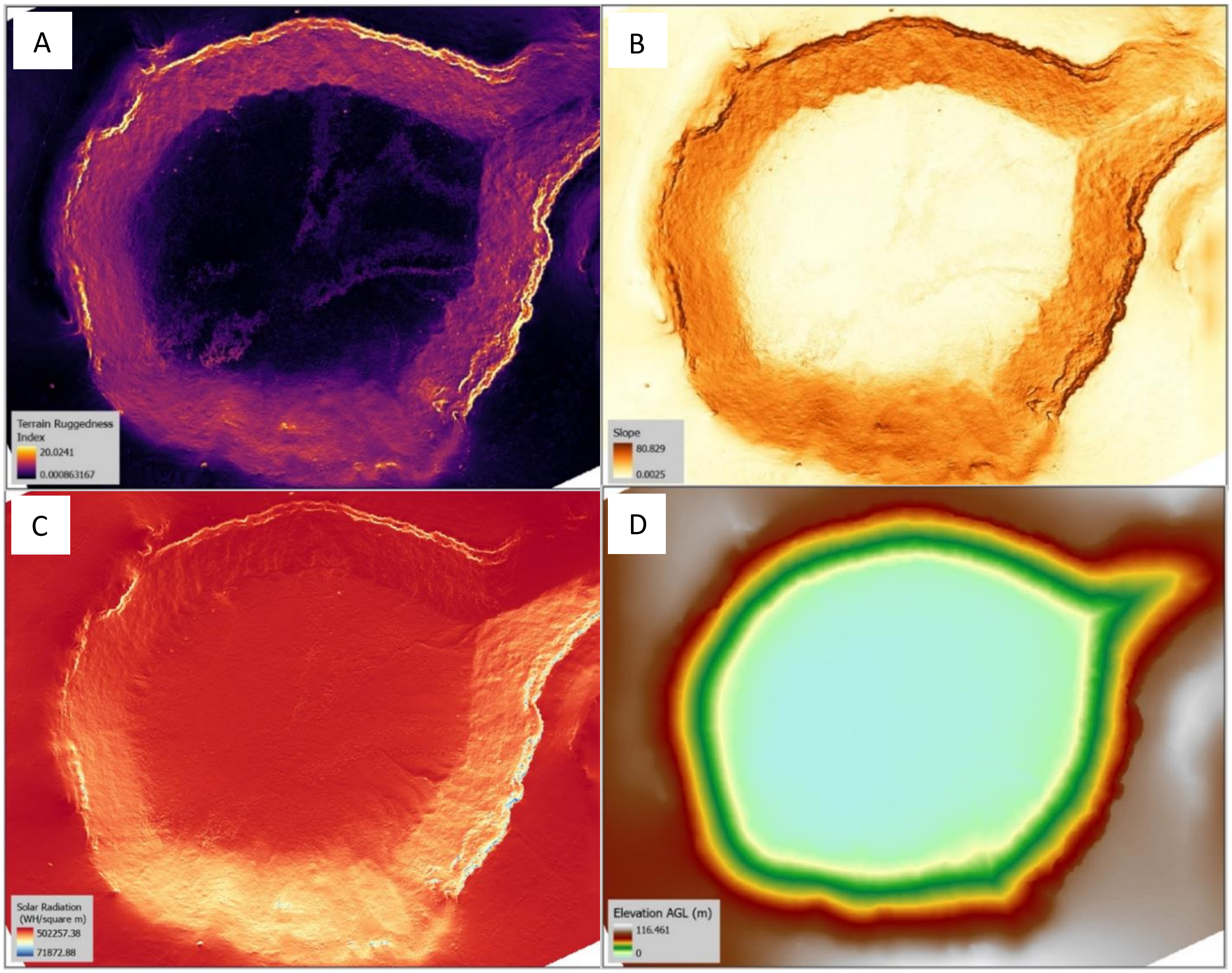

Figure 11. Layers for use in the nest site suitability model A) Terrain ruggedness index B) Slope C) Solar Radiation D) Height above crater floor

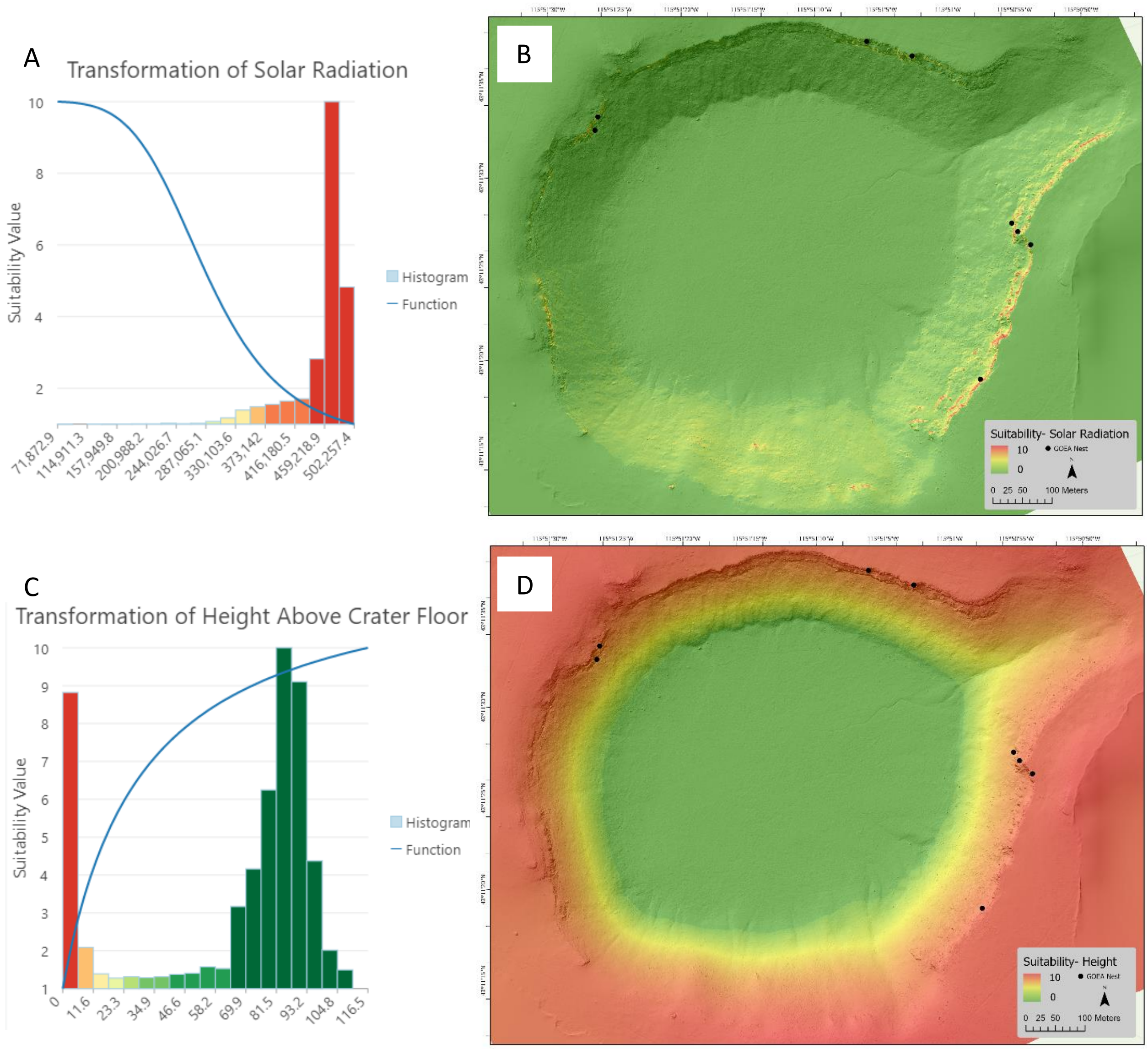

Figure 12. A) Transformation curve applied to solar radiation B) Transformed Solar Radiation C) Transformation curve applied to Height above crater floor D) Transformed Height Above Crater Floor

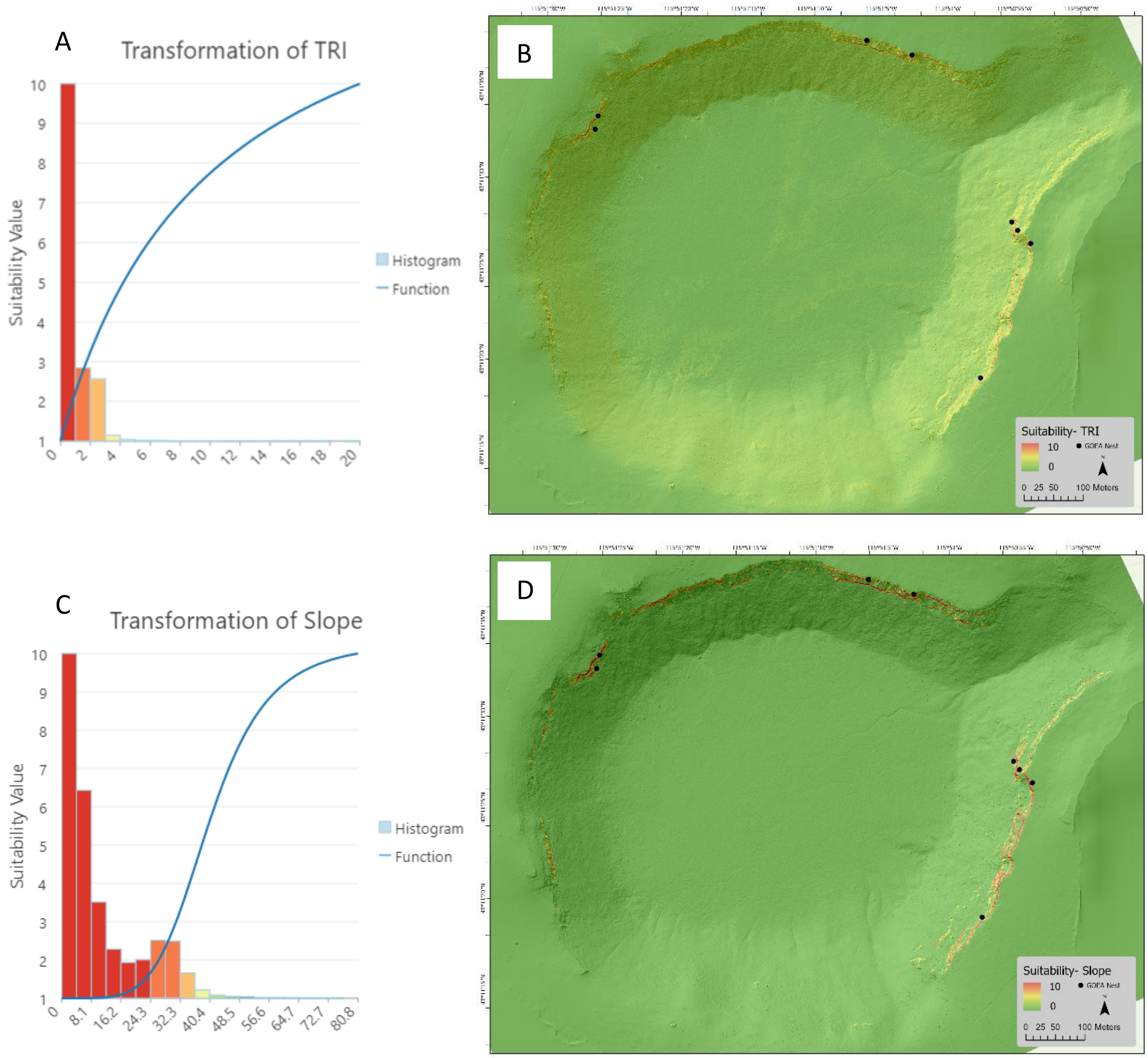

Figure 13. A) Transformation curve applied to TRI B) Transformed TRI C) Transformation curve applied to slope D) Transformed Slope

3.3.2. Final Model

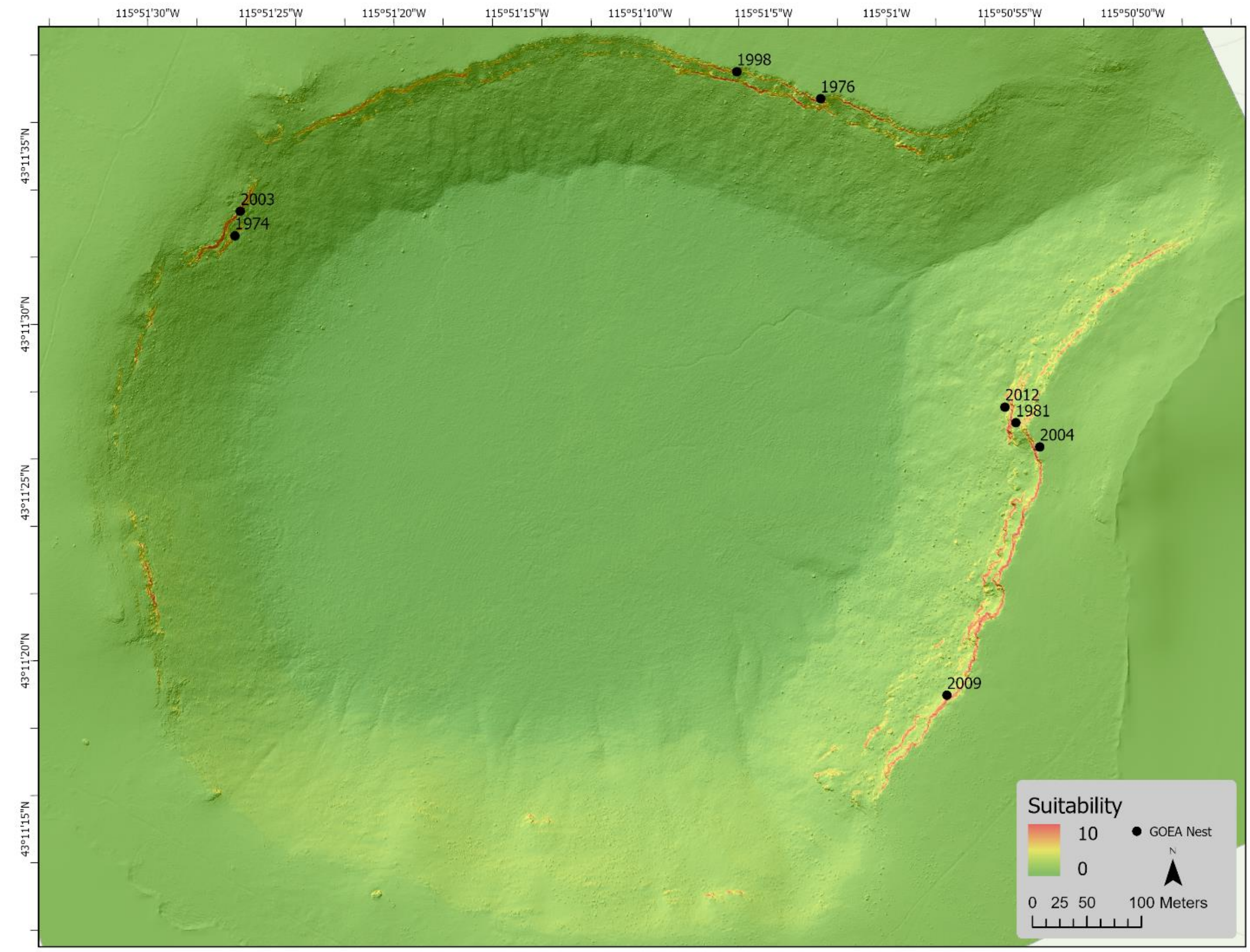

Figure 14. The final habitat suitability model in ArcGIS Pro created using the transformed slope, solar radiation, elevation above crater base, and TRI layers.

We created the final nest site suitability model (Figure 14. The final habitat suitability model in ArcGIS Pro created using the transformed slope, solar radiation, elevation above crater base, and TRI layers. and Figure 15) using terrain ruggedness index, slope, elevation, and solar radiation successfully assigned all areas of the large crater with documented Golden Eagle nests with a suitability score of 7.63 or greater; the highest nest site suitability was 9.06, and the average suitability value was 8.57. The highest suitability shown over the entire crater was 9.42 and the lowest was 0.31 (Table 4).

Table 4. Suitability values for each Golden Eagle nest at Crater Rings

Nest ID	1974	1976	1981	1998	2003	2004	2009	2012
Suitability Value	8.30	7.82	9.06	7.63	8.68	8.74	9.32	8.97

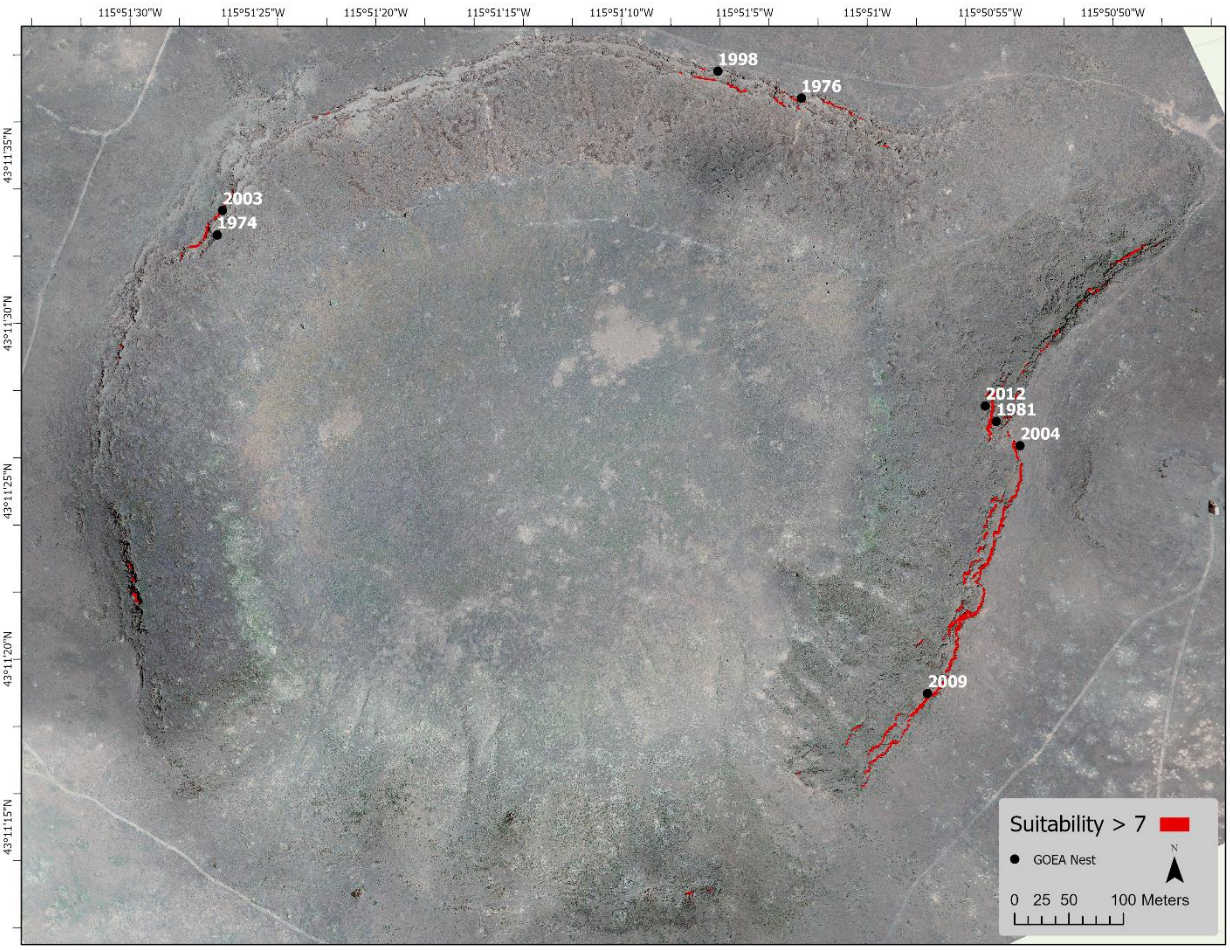

Figure 15. Orthomosaic of the big crater created from the UAS imagery with nest points and areas with a suitability greater than 7 shown in red.

3.3.3. Sensitivity Analysis

The sensitivity analysis demonstrated that while there were differences in the number of pixels classified as having a suitability of seven or greater or of eight or greater, the differences between the number of pixels with these values in the base model and the sensitivity models was not very large (Table 5). The biggest difference in suitable pixels was between the base model and the sensitivity model for elevation in pixels that have a suitability value of seven or greater. When we considered the overall size of the imagery (142 ha), this difference in pixel count is relatively minor. From the sensitivity models constructed, there does not seem to be any particular layer having an overly large effect on the model.

Table 5. Number of pixels with a suitability value of greater than 7 and greater than 8 when each layer's weight is increased by 9%.

	Suitability >7 (area in ha)	**Suitability >8 (area in ha)**
Base Model	1840 (0.184)	613 (0.0613)
TRI +9%	1646 (0.1646)	473 (0.0473)
Solar Radiation +9%	1668 (0.1668)	605 (0.0605)
Slope +9%	2001 (0.2001)	720 (0.072)
Elevation +9%	2067 (0.2067)	673 (0.0673)

3.3.4. Multispectral and Thermal Imagery

The random-forest classifications of the large crater into basalt, living vegetation, dead vegetation, and tumble mustard had accuracy values ranging between 0.462 and 1.0 based off the testing data (Figure 16). The living vegetation class had lower accuracy values than the other classes. This was likely due to patches of living vegetation being small during late spring when we collected the UAS imagery and thus it was probable the classifier had an inadequate number of pixels to train. There was also a large degree of mixing of living and dried vegetation, further confusing the classification between those two classes. However, the classifier did a good job of highlighting the built-up tumble mustard along the northern edge of the crater, especially near the 1998 and 1976 nests.

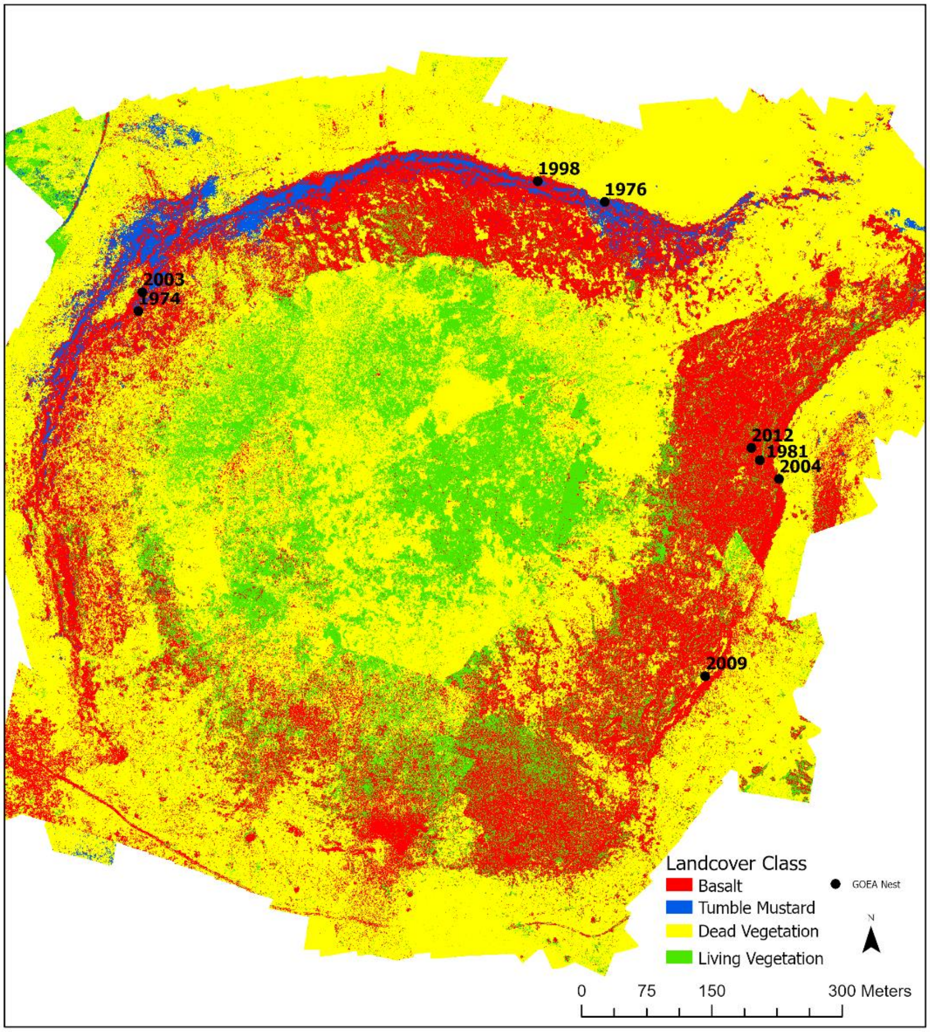

Figure 16. Random forest landcover clasification for each flight making up the large crater.

The thermal imagery captured by the MicaSense Altum was useful for reinforcing the accuracy of the solar radiation layer created using the DEM (Figure 17). There were differences in units and in what each was trying to show, however, both maps concluded that the areas where the Golden Eagle nests are located received less solar radiation than the surrounding areas. The agreement between the two layers supported our conclusion that the solar radiation layer created for the entire breeding period using the DEM was a good proxy for actual temperature.

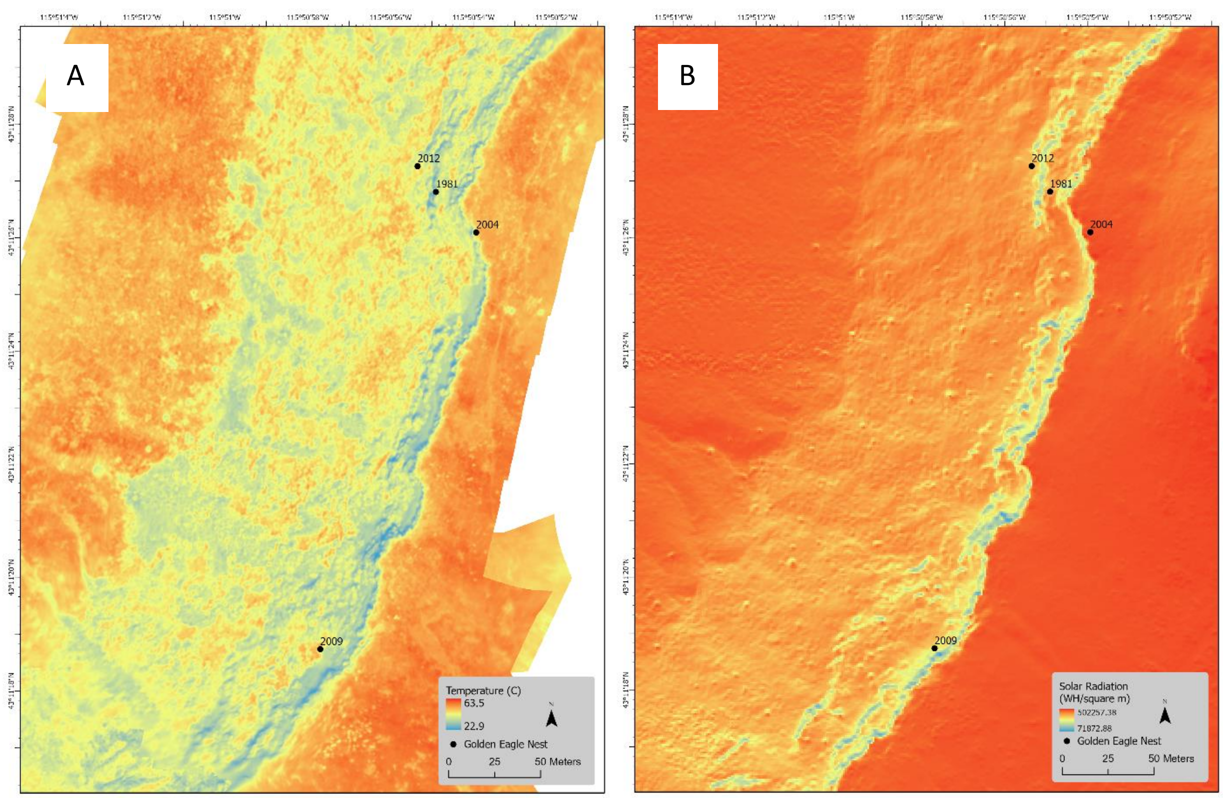

Figure 17. A) MicaSense Altum thermal imagery over Golden Eagle nests at Crater Rings B) Solar radiation layer derived from DEM over Golden Eagle nests at Crater Rings

3.4. Discussion

The results of this paper offer insights on how changing conditions in the NCA are affecting the available nest sites for Golden Eagles in the NCA. The vegetation classifications may explain why areas that otherwise seem to be good nesting habitat, yet nesting raptors are not utilizing them. Along with other exotic plants, tumble mustard has been present in southern Idaho since the early 1900s (Yensen, 1981) and with changing fire regimens, has continued to

Figure 18. A.) Buildup of Tumble Mustard on cliffs at large crater B.) Close-up of buildup

increase within the NCA (Yensen et al., 1992). The piles of tumble mustard built up on the norther crater rim are extremely dense and difficult to penetrate (Figure 18). Of the four Golden Eagle nests documented on the northern rim of the crater where the tumble mustard is blocking vast areas of the cliff, three are completely gone. The 1976 nest remains intact but has not been occupied by Golden Eagles since 2014. Because the raptors are unable to remove the brush to reach the cliff faces, the accumulations could be inhibiting nesting by Golden Eagles in areas where they have been found previously and that were otherwise classified as good nest sites. With this information provided by the classified MicaSense Altum imagery, we take note of cliffs obscured by tumble mustard to look at the relationship between the buildups of this invasive plant and continued Golden Eagle nesting. However, flying the MicaSense Altum over the entirety of nesting habitat along the snake river corridor would be expensive and time consuming. Because of this barrier, we developed our nest site suitability model using factors that we could derive from the DEM by using a simple RGB camera using SFM photogrammetry. In future models, we will consider including an aspect layer to exclude cliff areas where predominant winds deposit dried tumble mustard as a proxy for the classifications created with the MicaSense Altum imagery. The thermal layer provided by the MicaSense Altum helped confirm that the solar radiation layer was an accurate substitute for thermal imagery. The solar radiation layer derived from the DEM also allows for manipulations of the that may provide insight on how a warming climate will affect suitable nesting locations for Golden Eagles in the NCA.

As well as providing insights on the challenges faced by nesting Golden Eagles due to climate and landscape changes, the nest site suitability models are beneficial to land managers and biologists. Due to the large size of the NCA, efficiently searching for nests is challenging. However, when applied to the other cliff bands in the NCA, the nest site suitability model created in this pilot study will allow researchers to focus on the most suitable. It will also help biologists determine which areas for further protecting and monitoring in accordance with the resource management plan (BLM, 2008). In addition to benefiting biologists, the nest site suitability model is helpful for choosing areas in the NCA to capture in future UAS data collection flights as we expand the study from the pilot study area of Crater Rings to larger portions of the Snake River Canyon. While the continuous image created in this pilot study is visually compelling, it includes large swaths of the landscape that raptors do not utilize for nesting, such as the base of the crater and the grassy slopes leading up to the cliffs. In future efforts, confining the flights to only the cliffs that Golden Eagles use for nesting will increase the efficiency of the flights. While we did not document raptor stress due to the UAS flights in the craters, it would still be beneficial to raptors to restrict our time in the nesting territories and conducting flights in only the areas where nesting is possible.

Chapter 4. Comparing 3D Mapping Products from Different UAS Flight Patterns and Sensor Configurations

4.1. Introduction

Golden Eagles in the Morley Nelson Snake River Birds of Prey National Conservation Area (NCA) utilize ledges on the steep basalt cliffsides for nesting and rearing chicks (Steenhof et al., 1997). Accurately mapping the locations of nests on these cliffsides using traditional 2D, topographic maps can be challenging due to the inherent overhead perspective where contour lines merge tightly together to represent steep slopes. Similarly, vertical to overhanging terrain blocks nest sites from view in imagery collected aerially or by satellite from directly above. In addition, the steep slopes of the basalt cliffs cast shadows that obscure the cliff faces in imagery. When overlaid on 3D terrain models, for example in GE, the imagery appears stretched and distorted, completely obscuring nesting locations and making it difficult for observers to accurately pinpoint nest locations.

Structure from motion (SFM) photogrammetry is a technique that enables researchers to use a series of overlapping images from multispectral sensors or consumer grade cameras to create dense point clouds, multispectral orthomosaics, digital elevation models (DEM), and 3D models with greater temporal and spatial resolution than is available through platforms such as GE (Anderson and Gaston, 2013; Westoby et al., 2012). The imagery necessary for this technique can be captured on foot, from manned aircraft, and more recently, by uncrewed aircraft systems (UAS), making SFM accessible, economical, and applicable to different research needs including the study of avian nesting sites. Researchers have successfully used SFM with imagery collected by UAS to study small elevation variations in nesting sites of colonially nesting Gentoo Penguins (McDowall and Lynch, 2017), surface roughness and its relation to nest site selection by White-rumped Sandpiper (Korne et al., 2020), and erosion of cliff faces caused by nesting Burrowing Parrots (Genchi et al., 2015).

Even with the use of UAS, avoiding gaps and shadows in imagery of cliffs is difficult. By using flight patterns with multiple paths covering the cliff face, researchers have had success accurately representing cliffs in 3D using SFM (Dewez et al., 2016; Genchi et al., 2015). Researchers have warned against reckless experimentation with UAS when exploring wildlife biology applications as interest in the technology grows, demonstrating the need for cautious and ethical protocol development to prevent conflicts between UAS and wildlife (Hodgson and Koh, 2016) while creating high quality imagery that meets the needs of biologists. As UAS is increasingly used in wildlife research, there is a need to study the potential disturbance to wildlife, the ideal platforms and sensors, and best practices associated this new technology (Lambertucci et al., 2015).

The research goals of this paper were to compare the 3D mapping products that result from different combinations of flight patterns and sensors. We used terrain following and façade style flights paired with nadir sensors and obliquely faced sensors and compared the resolution, number of photos, and quality of the 3D models to determine which best captured the cliff faces without causing stretching, shadowing, and holes in the resulting products. We found that by pairing an oblique camera with a façade flight pattern, we were able to create an accurate digital replicate of the cliff face that researchers can use for documenting and studying nest locations.

4.2. Methods

4.2.1. Study Site

The study area for this research is the large crater of Crater Rings National Natural Landmark (Figure 19) which lies within the NCA in Southwestern Idaho (Figure 20). The 1952.4 km^2 Morley Nelson Snake River Birds of Prey National Conservation Area (NCA) in southern

Figure 19. The large crater at Crater Rings National Natural Landmark taken from the southwestern rim. Photo: E. Gregory

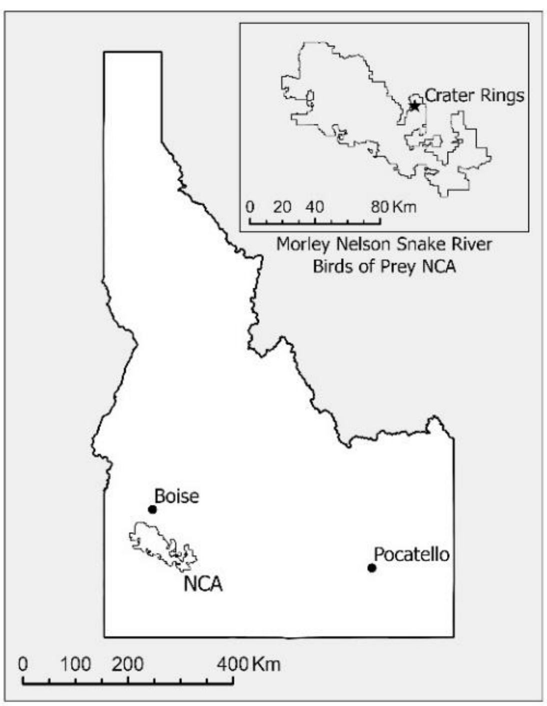

Figure 20. Morley Nelson Snake River Birds of Prey National Conservation Area and Crater Rings National Natural Landmark.

Idaho was created in August of 1993 to protect the densest population of nesting raptors in the United States (Public-Law 103-64). The Bureau of Land Management (BLM) manages the NCA, guided by the *Snake River Birds of Prey National Conservation Area Resource Management Plan and Record of Decision* (BLM, 2008). The NCA lies along the Snake River and experiences hot, dry summers and moderate winters. Between 1991 and 2020, the NCA received an average winter (December-February) precipitation of 6.07 cm and had an average winter temperature of 1.94 ˚C. Average summer (June-August) precipitation was 2.54 cm and average summer temperature was 24.5˚ C (NOAA, 2020). The plant community consists of Sagebrush (*Artemisia* spp.), Rabbitbrush (*Ericameria nauseosa*), Bitterbrush (*Purshia tridentata*), Winterfat (*Krascheninnikovia lanata*), Shadescale (*Atriplex confertifolia*), native grasses, and increasingly Cheatgrass (*Bromus tectorum*) and other invasive plants (Kochert and Pellant, 1986). In addition to providing habitat for large populations of raptors, the NCA is home to abundant prey species such as Piute Ground Squirrel (*Urocitellus mollis*) and Black-tailed Jackrabbit (*Lepus californicus*) (Kochert and Pellant, 1986). The twin craters provide excellent nesting locations for Golden Eagles (*Aquila chrysaetos*), Prairie Falcons (*Falco mexicanus*), and Red-tailed Hawks (*Buteo jamaicensis*) as well as Common Ravens (*Corvus corax*). We chose the larger crater as the study area for this project because of the occupied Golden Eagle nest along the crater wall, ease of access, and density of other known nesting birds. We collected the imagery for this project over the spring of 2020 and the spring of 2021.

4.2.2. Data Collection Methods

4.2.2.1. Nest Site Locations

In the early spring of 2020, biologists from Boise State University (BSU) surveyed the crater for nesting raptors and observed one pair of Golden Eagles, three pairs of Prairie Falcons, and one pair of Common Ravens nesting along the walls of the craters. They recorded the nest locations using consumer grade, handheld global positioning system (GPS) from directly above, below, or within the nest and refined the nest points using Google Earth (GE). As UAS image collection operations were underway in the late spring and summer of 2020, the same biologists were present to observe and record behavioral data on the nesting raptors at the craters. They watched for signs of stress such as adults leaving the nests for abnormally long periods of time, excessive calling, and attempts to interfere with the UAS to prevent conflict and to provide insight on the reactions of breeding raptors in the NCA to the presence of UAS. In the spring of 2020, we had four biologists spread along the rim observing for signs of disturbance. In the spring of 2021. The UAS Pilot in Command observed the flights closely to watch for signs of distress.

4.2.2.2. Platform and Sensors

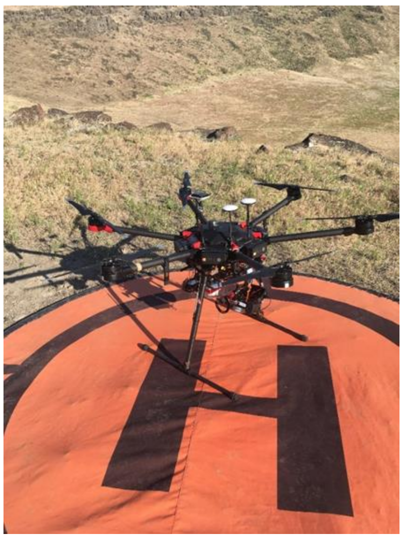

Figure 21. The Matrice 600 Pro equiped with three Sony Alpha a6000 cameras.

We conducted the 2020 flights using a Matrice 600 Pro (SZ DJI Technology Co., Ltd) (Figure 21) equipped with either three digital mirrorless cameras or a single digital mirrorless camera (Sony Alpha a6000), depending on the flight, to collect Red-Green-Blue imagery. The Sony Alpha a6000 camera has the following specifications: 16 mm lens, 23.5 x 15.6 mm (APS-C) CMOS sensor, a 3:2 aspect ratio, 24.7 megapixel actual sensor resolution, and 24.3 megapixel effective sensor resolution (Sony, 2021). We attached one camera facing nadir and faced the remaining two obliquely out to the sides at approximately 75˚-80˚ (Figure 22 A). Because of the challenges associated with capturing cliff faces, we hoped to investigate the differences in imagery collected by a single nadir camera compared to obliquely angled cameras in addition to the nadir one. The settings for the Sony Alpha a6000 camera were set to focal point of infinity, f-stop of four, shutter speed of 1/800, and ISO of 100.

We conducted the 2021 flights using a Phantom Pro UAS (Figure 22 B) and its onboard,

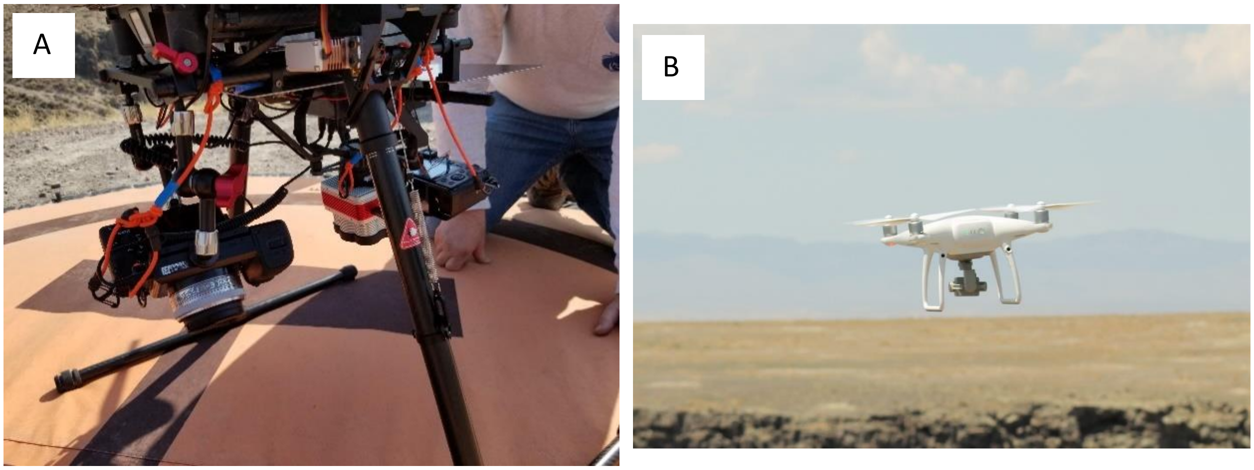

Figure 22. A) Matrice 600 Pro payload: 3 Sony Alpha a6000 cameras B) Phantom Pro 4 UAS

obliquely faced camera. The phantom camera specifications include: 1-inch 20 megapixel CMOS sensor, a FOV 84° 8.8 mm/24 mm lens, and image size of 3:2 (DJI, 2021). We controlled the angle of the camera, which can move from 65˚ to 90˚, during the UAS flights and aimed it to maximize the amount of cliff face collected in the images while remaining as close to 90˚ as possible.

4.2.2.3. Mission Planning and Flights

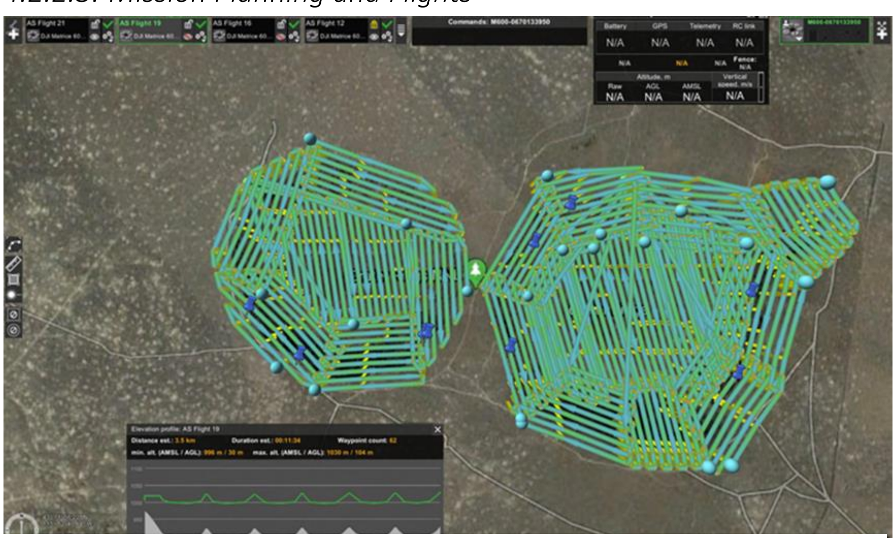

Figure 23. The flight paths planned to cover each crater at Crater Rings in Universal Ground Control Software (UGCS)

We obtained permission from the BLM for conducting UAS flights in the NCA and fulfilled the necessary Institutional Animal Care and Use Committee (IACUC) protocol prior to data collection for both the 2020 and 2021 field seasons. We conducted the UAS data collection on May 28th and 29th, 2020 using the Matrice 600 Pro and on June 18th, 2021 using the Phantom Pro.

We planned all flights using Universal Ground Control Software (UGCS). With the Matrice 600 Pro, we collected imagery from an elevation of 100 meters AGL over the entirety of the crater with a nadir Sony Alpha a6000 digital mirrorless camera using terrain following mode (Figure 23) (Table 6). To ensure 75% sidelap in the photos, we set the side distance to 22 m and the flight speed was 5m/s. I will refer to this flight as “nadir”. In addition to the 100 m elevation imagery, we collected imagery in the area surrounding the Golden Eagle nest at a flight height of 60 m using the Matrice 600 Pro with three Sony Alpha a6000s (Figure 24). We attached two cameras at oblique angles, and one pointing nadir (Figure 22 A). To ensure 75%

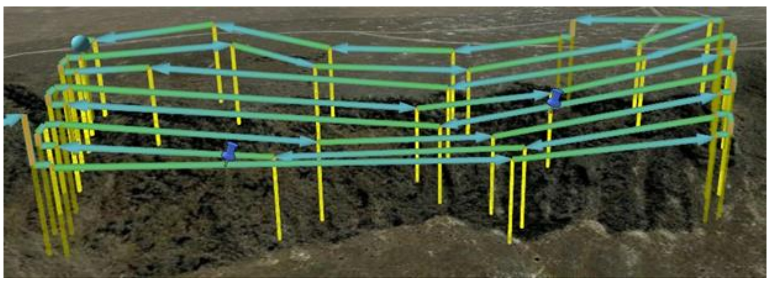

Figure 24. The 60 m flight path over the occupied and historical Golden Eagle nests at Crater Rings.

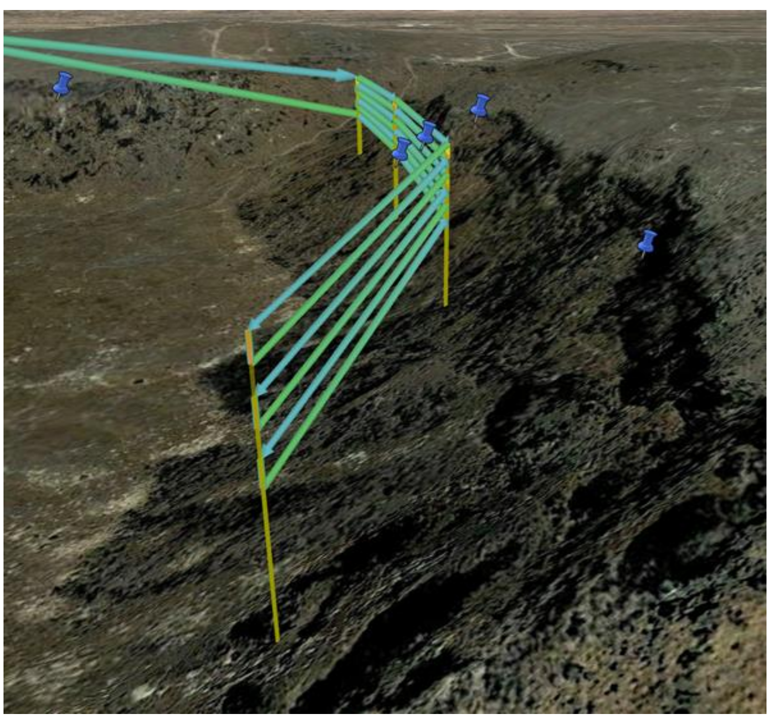

Figure 25. Façade flight pattern over occupied Golden Eagle nesting area at Crater Rings

sidelap, we set the side distance to 18 m for the 60 m images. I will refer to this flight as "multiangle". The flight speed was 5 m/s for both the nadir and multiangle flights. In UGCS, we used the terrain following tool to plan the nadir and multiangle flights using the default DEM provided, which is from the Shuttle Radar Topography Mission (SRTM) and has a resolution of one arc second (approximately 30 m).

Table 6. Metrics for the three UAS flight styles at Crater Rings

	Nadir	**Multi-angle**	**Façade**
UAS Platform	Matrice 600 Pro	Matrice 600 Pro	Phantom Pro 4
Camera	1 nadir Sony Alpha a6000	2 oblique and 1 nadir Sony Alpha a6000	1-inch 20-megapixel CMOS sensor
Flight Height	100 m	60 m	50 m
Flight Pattern	Terrain following	Terrain following	Façade

Using the Phantom 4 Pro, we collected imagery 50 m from the cliff face using the façade scanning tool in UGCS (Figure 25). This tool plans flights with the UAS flying in a pattern parallel to the vertical cliff face with the default SRTM DEM. We limited imagery collection to the cliff bands raptors use for nesting and used the onboard 1-inch 20-megapixel CMOS sensor to take photos (Table 6). We set both the forward and side overlap to 75% and the flight speed to 3.4 m/s. We adjusted the minimum and maximum flight heights depending on the height of the cliffs and the steepness of the hillside leading up to the cliff. I will refer to this flight as "façade".

4.2.3. Image Processing

Because of differing lighting conditions throughout the time when we collected imagery, we used Adobe Lightroom to even out the exposure of the images from the nadir flights. No pre-processing was necessary for the multiangle and façade flight imagery because the lighting conditions were consistent. We used structure from motion photogrammetry in the software Agisoft Metashape Pro to create georeferenced orthomosaics, digital elevation models (DEM), dense point clouds, tiled model, and 3D models of the entire large crater using the nadir flights, the Golden Eagle nesting area with the multiangle flight, and of the cliff bands using the façade flights. For all imagery collected with the Sony Alpha a6000 cameras, we used ground control points collected in the crater to put the products into a proper coordinate system for further analysis. The imagery collected with the Phantom Pro was georeferenced using the onboard GPS. In Agisoft Metashape Pro, we performed the alignment with high accuracy and built the dense point cloud with the quality set as high for all imagery sets. To create the DEM, tiled model, and 3D model, we used the dense point cloud as the source data. We generated reports in Agisoft Metashape Pro to provide metrics on the accuracy, area, and ground resolution of the products resulting from the nadir, multiangle, and façade flights.

After creating the structure from motion products in Agisoft Metashape Pro, there were areas of inconsistent lighting in the orthomosaic created using the nadir flights, due to changes in cloud cover throughout the days. We were able to even out the shadowing in these areas using Photoshop to create an evenly exposed image of the entire crater. We exported the final image from ArcGIS Pro as a KML and then tiled it to display in Google Earth Pro. Over the tiled orthomosaic, we displayed other layers including buffers around occupied nesting areas, nest locations, ground control points, and areas containing the most suitable nesting locations as determined in the previous chapter.

4.3. Results

4.3.1. Visualization

The nadir flight resulted in 13,800 images covering the entire large crater, a total of 152 ha. The ground resolution was 3.31 cm/pixel and the reprojection error was 0.437 pixels (Table 7). The point cloud from this flight had large holes over the cliff bands (Figure 26 A) that translated to large dark areas in the 3D model (Figure 27 A). The multiangle UAS flight resulted in 869 images covering 0.0832 ha directly over the occupied Golden Eagle nest. After SFM, the ground resolution of the resulting products was 2.29 cm/pixel, and the products had a reprojection error of 0.788 pixels (Table 7). The dense point cloud from this flight had some shadowing in areas with overhanging cliffs, but no obvious holes (Figure 26 B) and the corresponding 3D model was much more complete than the model from the nadir flights (Figure 27 B). The façade flight resulted in 928 photos of the north rim of the crater and 316 photos of the southeast rim of the crater. The ground resolution of the flight over the north rim of the crater was 1.32 cm/pixel and over the southeast rim was 1.14 cm/pixel, and the reprojection error for the north rim was 0.785 pixel and 0.764 pixel for the southeast rim (Table 7). Like the multiangle flights, the dense cloud from the façade flight was continuous and had no large holes (Figure 26 C) and the 3D model had few visible holes (Figure 27 C). In all three datasets, there were more than nine overlapping photos

Table 7. SFM results for the three flights at Crater Rings

	Nadir	**Multiangle**	**Façade (north rim/southeast rim)**
Number of Photos	13,800	869	1,244
Area Covered (ha)	152	8.32	49.46
Ground Resolution (cm/pixel)	3.31	2.29	1.32/1.14
Reprojection Error (pixels)	0.437	0.788	0.785/0.764

for all areas in the flight excluding the edges where the UAS turned in flight. In the façade 3D model, the Golden Eagle nest is visible. In the nadir, multiangle, and currently available 3D imagery through GE, the nest is covered by shadows and holes due to the steep and overhanging cliffs or is not discernable because of lower resolution (Figure 28). In addition to the 3D products, the nadir flights yielded a seamless orthomosaic of the entire crater which we used in Google Earth Pro (Figure 29). We displayed the high quality orthomosaic along with nest points, GCP, buffers around nests to protect nesting raptors, and areas containing suitable nesting locations from the previous paper.

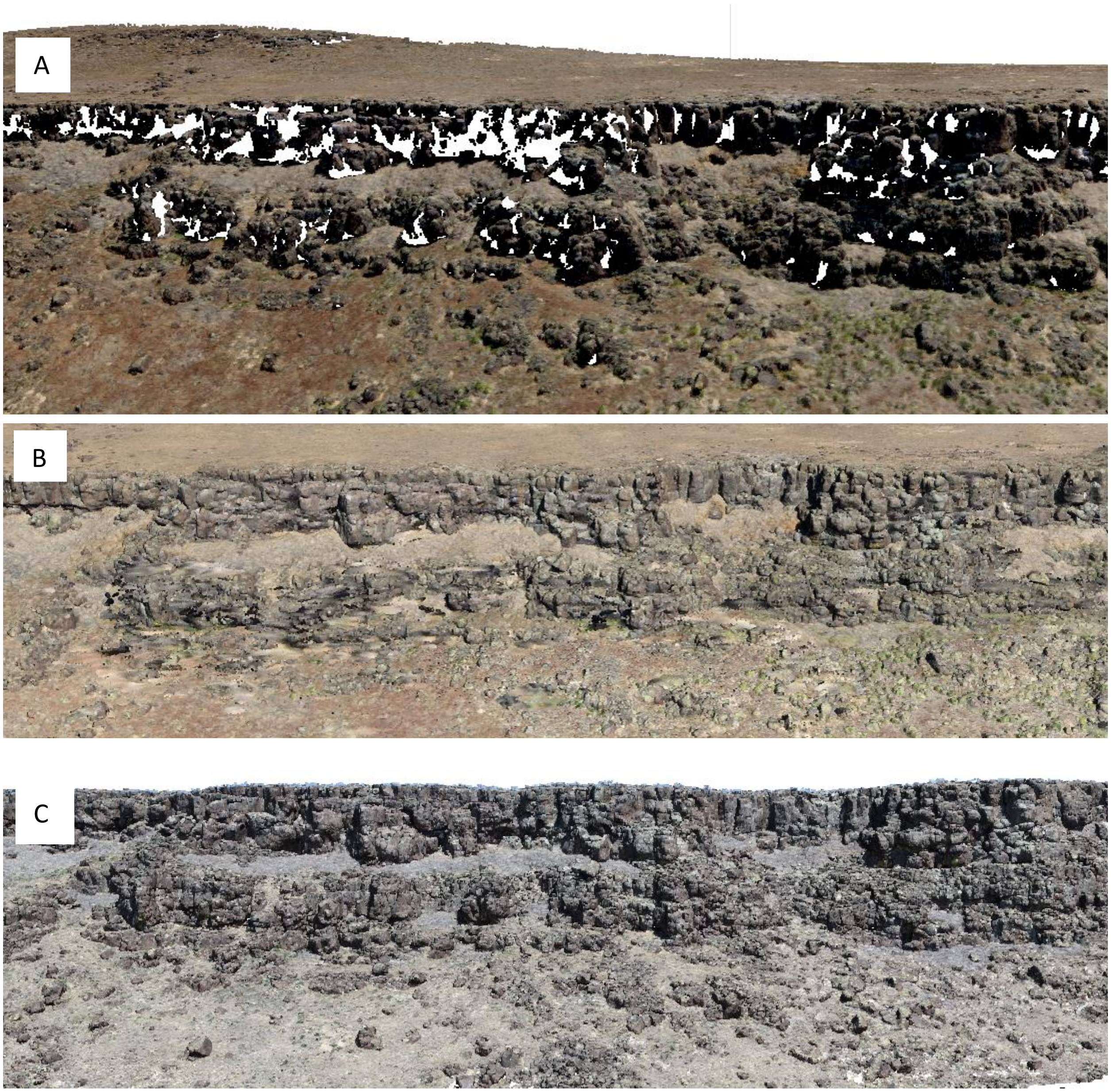

Figure 26. Dense point clouds from the three flight styles at Crater Rings. A) Dense cloud from the nadir flight B) Dense cloud from the multiangle flight C) Dense cloud from the façade flight

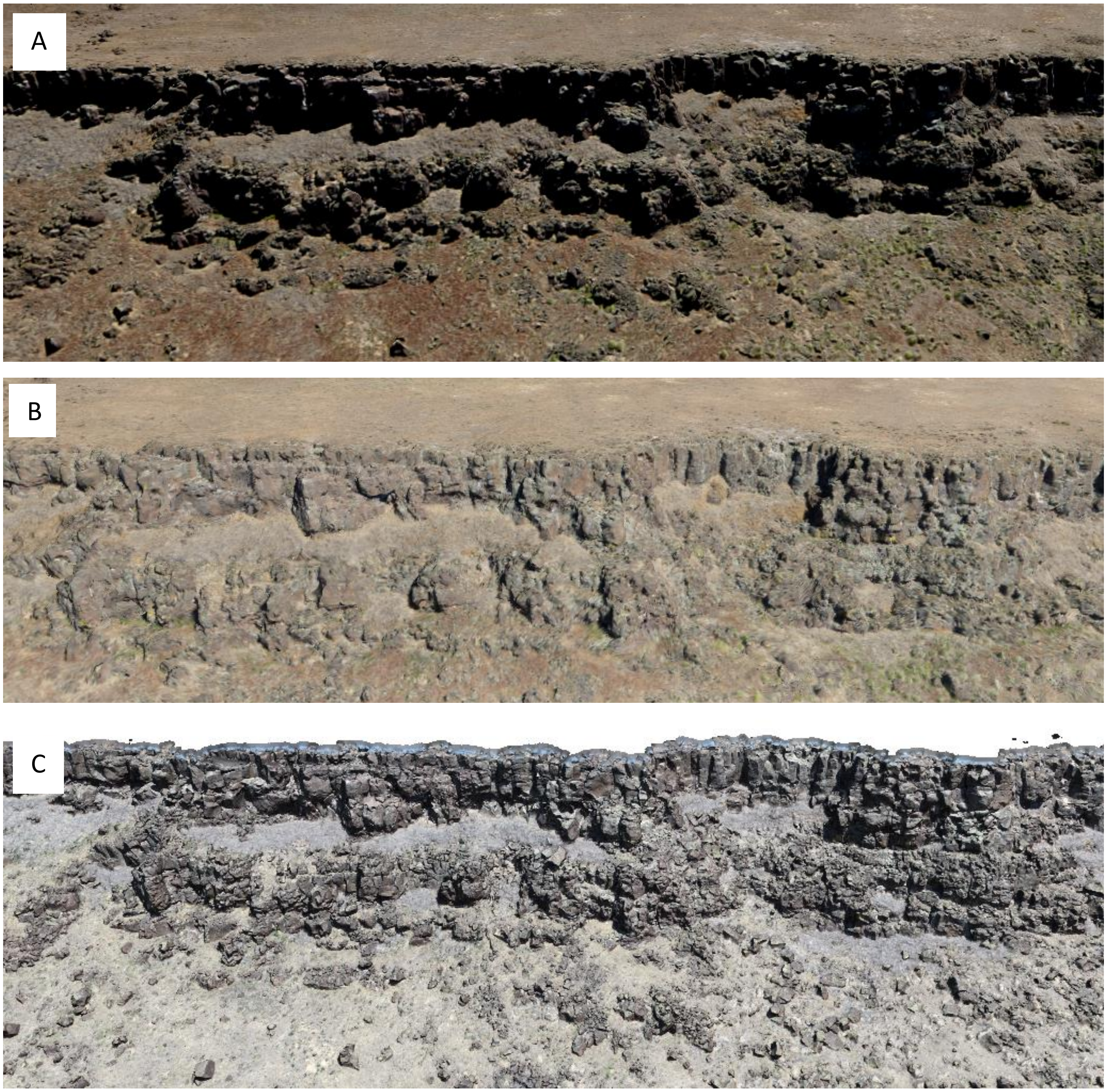

Figure 27. Samples of the 3D models from A) the nadir imagery, B) the multiangle imagery, and C) the façade imagery

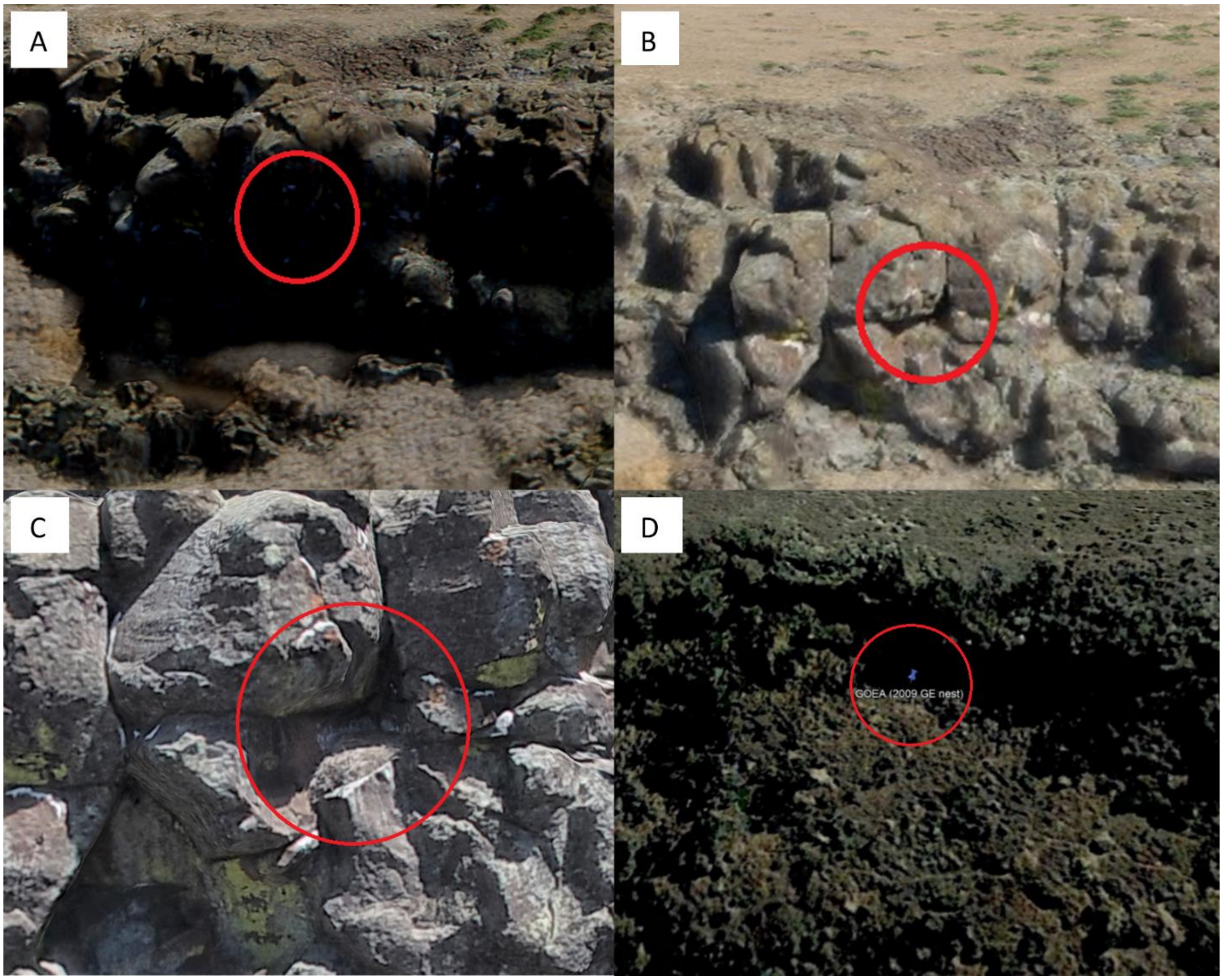

Figure 28. Location of the 2020 Golden Eagle nest at Crater Rings in A) nadir model B) multiangle model C) façade model D) GE

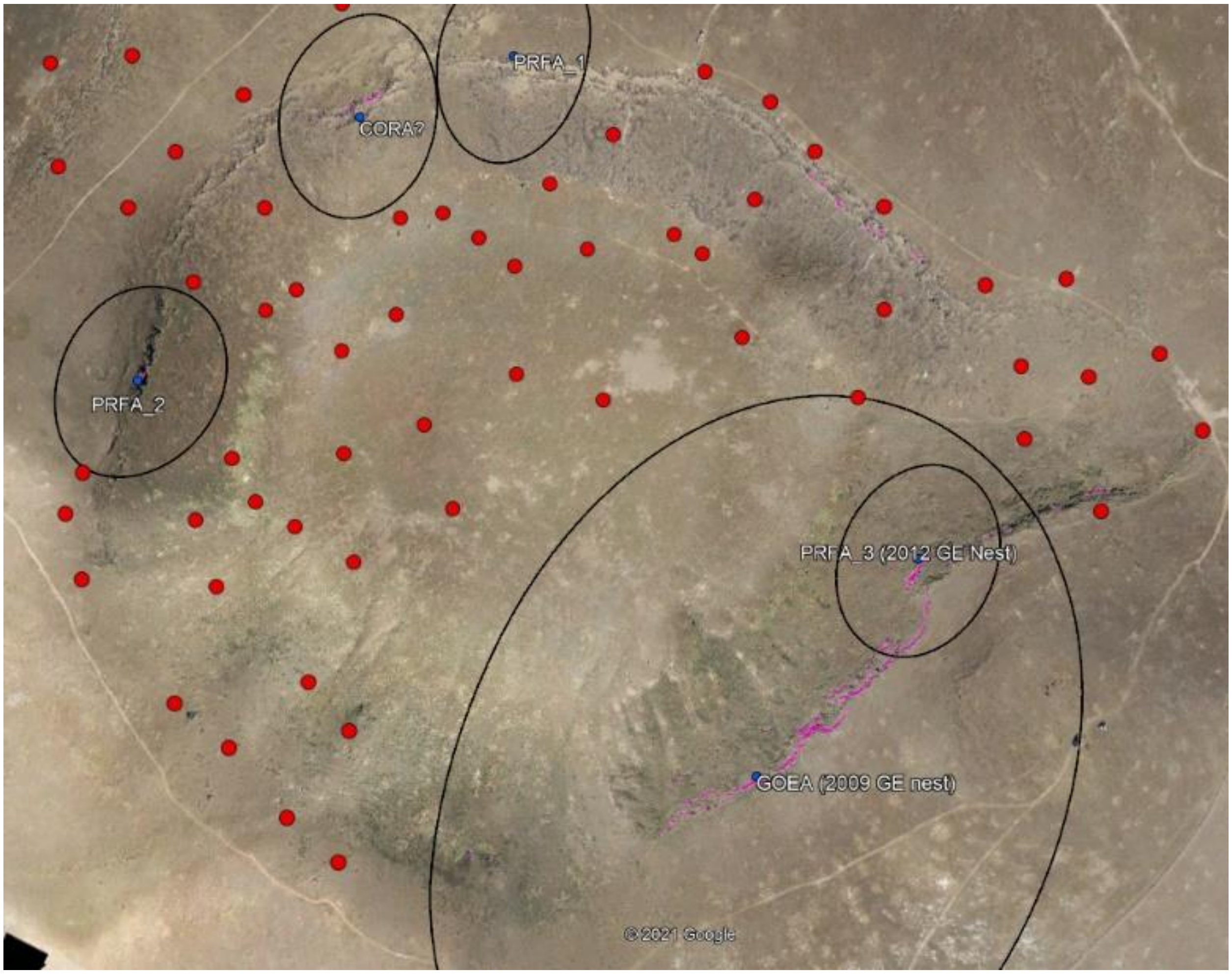

Figure 29. The orthomosaic covering the large crater displayed in Google Earth Pro with ground control points, nest locations, nest buffers, and suitable habitat.

4.3.2. Raptor Response

The raptors had no visible reaction to the nadir and façade flights. The resident Prairie Falcon pairs at the large crater did not visibly react to the drone flight and went about hunting and attending nestlings as usual. On-site observers did not see one Golden Eagle adult from mid-morning until we left the study site in the evening on the 28th of May. However, the second adult of the pair sat in the nest for the entirety of the day while we flew and did not react to the UAS during the nadir or multiangle flights. The only reaction we observed was from a Prairie

Falcon during the multiangle flight when it dove and got within 20 m of the UAS. However, the Prairie Falcon quickly changed direction and the UAS Pilot in command did not have to perform evasive maneuvers.

4.4. Discussion

4.4.1. Visualization

Researchers in the NCA have gone through many changes in how they record raptor nest locations as technology has advanced, most importantly, the transition from paper maps to digital mapping platforms. The currently available 3D mapping products available through Google Earth do not offer the resolution necessary for mapping precise nest locations and have shadows and stretching that obscure the nests. The high-resolution 3D models created with SFM and façade flight patterns make it possible to refine historical nest points and avoid creating duplicate nest points as they continue monitoring efforts in the NCA. In addition to the 3D mapping products, the orthomosaics when viewed on tablets or phones can be combined with other layers such as those showing suitable nesting locations and with buffers around occupied nest sites, to ensure that researchers have access to accurate data when searching for new nests and monitoring existing ones.

While it created an effective visual to map the entirety of the crater, due to the time required to collect the data, manually refine ground control placement, and process the large volume of photos, it is most efficient to map only the cliff bands where raptors nest as opposed to the grassy slopes below the cliffs in future work. In addition, the overhangs that protect the nests from rain, sun, and predators prevent nadir sensors from capturing complete imagery of the cliff faces, and to a lesser degree by the oblique sensors when they are flown in a terrain following pattern. Because of the reduction in coverage, we found that it is best to use a façade flight pattern directly parallel to the cliff wall. The façade style flight allowed us to create an accurate 3D model with few shadows, minimal stretching, and high resolution and will be used in the future to map the areas where birds are actively nesting or likely to nest. Although this method does not create a continuous map of the area, it allows us to collect and process high resolution imagery of the nest sites more efficiently and captures imagery with the fewest holes where cliffs are overhanging. Although the multiangle and façade flight patterns had a smaller field of view and required slower flights, the ground resolution of 2.29 cm/pixel provided by the multiangle dataset and between 1.32 and 1.14 cm/pixel provided by the facade dataset is better for viewing accurate nest locations than the 3.25 cm/pixel resolution from the nadir dataset. This lends further support to the idea of only mapping areas of greatest importance to nesting raptors and doing so using closer flights, flight patterns, and sensor configurations that best capture the cliffs.

4.4.2. Raptor Reactions and Implications for Further Studies

The lack of reaction aside from the single incident with the Prairie Falcon was unexpected as we set out to perform this research. It is likely that the reactions of the nesting raptors would change depending on the point in the breeding season during which the birds were disturbed. Broadly speaking, bird species including raptors are increasingly aggressive in their defense of nests and nestlings as the breeding season progresses, likely a reflection of the time and resources expended caring for their young (Redondo, 1989). It is possible that we were conducting flights early enough in the season where the Golden Eagles were not exceptionally protective of their young, but they may be more aggressive later in the season. It is also possible that the proximity of the study area to Mountain Home Air Force Base desensitized the resident raptors and caused them to be more tolerant to a variety of aerial vehicles.

Chapter 5. Conclusions

5.1.1. Nest Site Suitability Modelling

The nest site suitability model created from the digital elevation model (DEM) accurately showed the areas occupied by Golden Eagles for nesting as highly suitable at the large crater of Crater Rings National Natural Landmark. Because of the cost, processing power, and time required to fly multispectral sensors, we chose to develop a nest site suitability model based on a DEM that can be created using simple RGB imagery and structure from motion (SFM) photogrammetry. This type of UAS platform is accessible to all users and is low cost. In future work, we will test this model across the greater Snake River Canyon to determine if it is widely appropriate for predicting suitable Golden Eagle nesting locations in the Morley Nelson Snake River Birds of Prey National Conservation Area (NCA). By applying the nest site suitability model to larger regions of the NCA, researchers and land managers will be able to focus their efforts on the areas where occupancy is most likely. The suitability model also provides an opportunity to determine how nest sites and cliffsides are affected by changes in individual nest site suitability characteristics. In particular, as the climate continues to change, nest sites along cliffs will receive more in solar radiation over the course of a breeding season. With this nest site suitability model, we will be able to apply the predicted increase in temperature to determine what areas will continue to be suitable for Golden Eagle nesting in the future and which sites will be lost due to unsuitable conditions. With this information land managers can monitor nesting sites and ensure those remaining sites continue to be protected.

Another important consideration for the future iterations of the model will be determining why Golden Eagles do not nest in some areas of the cliffsides that were identified as being highly suitable. At the large crater, the cliffsides without occupied nests aligned with regions with large buildups of dried tumble mustard along the crater walls. The buildups of these invasive plants may be blocking otherwise suitable nest sites. We will investigate the utility of including an aspect layer in the nest site suitability model to account for the tumble mustard blown into piles by the predominant winds in the NCA.

5.1.2. Flight Operations for Capturing Cliff Faces

Our Uncrewed Aircraft Systems (UAS) flights at Crater Rings showed that using a façade flight pattern combined with an obliquely faced camera was the best approach for collecting imagery with few gaps over the cliff faces. The nadir flight created a compelling image of the entire crater but had large holes in the dense point cloud and 3D model over the cliff faces that Golden Eagles use to nest. The multiangle flights resulted in more complete imagery but at a lower resolution than the façade flight pattern. While the imagery from the multiangle approach was more complete, it also required a great deal of computing power to process the photos from three individual cameras. Moving forward, UAS surveys of the cliffs in the NCA will use a façade style approach to collect the most complete imagery possible of the cliffs used by Golden Eagles for nesting.

5.1.3. Use of UAS with Raptors

Similar to other researchers utilizing UAS for studying birds of prey, we did not encounter any conflicts during data collection. By ensuring that the nestlings were old enough to thermoregulate but not close to fledging, we hoped to cause as little distress to the nestlings as possible. The adult Golden Eagles in the area did not seem to be affected by the presence of UAS around the nest sites. The Prairie Falcons nesting in the area also seemed unbothered by the UAS aside from one approach that was quickly reversed prior to action being taken by the

UAS pilot in command. It is possible that later in the nesting season adult birds would react more aggressively to UAS in their territories. Moreover, it may be that the birds in the NCA are acclimated to aircraft due to the proximity of the NCA to Mountain Home Air Force Base. We believe that future studies of raptors in the NCA will be able to successfully use UAS if they maintain a respectful distance from nests and perform studies during the portions of the breeding season least likely to disturb nesting activities.

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