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Landsat Evaluation Of Trumpeter Swan Historical Nesting Sites In Yellowstone National Park

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LANDSAT EVALUATION OF TRUMPETER SWAN

HISTORICAL NESTING SITES IN YELLOWSTONE NATIONAL PARK

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DEDICATION

This thesis is dedicated to my family and friends
for their unwavering support during this adventure.

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ABSTRACT

Keywords: *Cygnus buccinator*, image analysis, Landsat, NDVI, trumpeter swan.

The trumpeter swan (*Cygnus buccinator)* has historically nested in the Greater Yellowstone Ecosystem of Montana, Idaho, and Wyoming. Declines in habitat quality may be limiting the growth of the Tri-State Flock. The purpose of this study was to map historical nesting areas for trumpeter swans in Yellowstone National Park (YNP) and evaluate Landsat images for changes to habitat. Historical nesting sites were evaluated through image classification and Normalized Difference Vegetation Index (NDVI) and compared to field conditions. Swan nesting records were analyzed in comparison to drought index and human visitation rates to determine if these factors may contribute to the decline of trumpeter swans nesting in YNP.

Vegetation type and water quality were evaluated at 36 wetlands identified as historical nesting locations. Potamogetonaceae was the largest family represented in plant samples and had the highest frequency of occurrence in samples. There was no significant difference in whether swans were present or absent in wetlands with regards to water quality parameters tested or physical parameters identified. There was an association between certain drought index values and the number of cygnets fledged and the number of territories occupied by swan pairs.

I was unsuccessful in using image classification to define pixel characteristics common among historical nesting territories of swans in YNP based on 5 Landsat images from 1975, 1979, 1990, 1999, and 2005. I was also unable to distinguish aquatic plant species composition, emergent and submergent plants, open water versus aquatic vegetation, wetland classification, or swan preference using image classification. No relationship was found in a regression model of NDVI values and swan pair occupancy or number of swans fledged, with the exception of a weak, positive relationship between pair occupancy and positive NDVI values, and a strong, positive relationship between swan fledge rates and positive NDVI values derived from the 1990 image. Landsat images currently appear to be unreliable in predicting swan pair occupancy or fledging

success of nesting pairs. NDVI calculations were not consistently reliable in predicting relationships with swan pair presence or fledge success in nesting territories of YNP, but significant relationships did indicate that factors which might influence swan pair occupancy and fledge rates may be monitored through continued use of NDVI calculations.

There was a significant curvilinear relationship between human visitation rate and the number of territories occupied by pairs of swans, the number of territories that fledged cygnets, and the number cygnets fledged, which was particularly evident in years with high visitation rates and poor swan productivity. There was no significant difference in the number of swans fledged in areas near park trails or near park roads compared to more remote locations, and swan fledging was independent of proximity to remote or visitor-accessible areas.

A goal of this study was to provide park managers with a method for assessing habitat quality that might be used to monitor nesting trumpeter swans in YNP. Image classification of nesting wetlands did not provide a useful model of areas suitable for nesting trumpeter swans, but NDVI classification has the potential to provide information useful in long-term monitoring of factors which may influence swan nesting. While no overall trends were observed through Landsat modeling, continued analysis could provide information to park managers in terms of the quality of individual nesting sites and changes over time. Climate change predictions and human visitation impacts can be incorporated to provide managers with the information they need to make decisions regarding the future of nesting trumpeter swans in YNP.

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LIST OF ABBREVIATIONS

Canada Flock	CF
Degrees of Freedom	d.f.
Enhanced Thematic Mapper Plus	ETM+
Geographic Information System	GIS
Grains per gallon Calcium Carbonate	gpg ($CaCO_3$)
Multispectral Scanner	MSS
Normalized Difference Vegetation Index	NDVI
National Oceanic and Atmospheric Administration	NOAA
National Park Service	NPS
National Weather Service	NWS
National Wetland Inventory	NWI
Palmer Drought Severity Index	PDSI
Rocky Mountain Population	RMP
Significant Difference	S.D.
Satellite Pour l'Observation de la Terre	SPOT
Thematic Mapper	TM
Tri-state Flock	TSF
United States Department of Agriculture	USDA
United States Fish and Wildlife Service	USFWS
United States Geological Survey	USGS
Wyoming Game and Fish Department	WGFD
Yellowstone National Park	YNP

CHAPTER 1

INTRODUCTION

The trumpeter swan (*Cygnus buccinator*) is the largest species of waterfowl (Family: Anatidae, Tribe: Cygnini) with a wing span up to 2.4 m and weighing up to 13.5 kg (Slater 2006). Historically, the breeding range extended from Alaska, east to Hudson Bay, south to Mississippi and Arkansas, and west to California (Figure 1[A], United States Department of Agriculture [USDA] 2002). By the early 1900s, the population had suffered a noticeable decline due to overharvesting by settlers for skins and food (Banko 1960, Shea et al. 2002, Proffitt et al. 2009). In 1932, a total of 69 trumpeter swans existed within the contiguous United States (Anderson et al. 1986); 31 swans were located within the boundaries of Yellowstone National Park (YNP), 26 were located west of YNP in Centennial Valley, and 12 elsewhere in the Tri-state Region, an area geographically located near the south-western Montana, eastern Idaho, and north-western Wyoming boarder (Figure 2; Bellrose 1976). Red Rock Lakes National Wildlife Refuge in Montana, west of YNP, was created in 1935 for the purpose of preserving breeding habitat for the remaining Tri-state Flock (TSF; Banko 1960). Nesting records for YNP date back to 1931, when young were fledged from Trumpeter Lakes, East Tern Lake, and Shoshone Lake (R. Shea, pers. comm.). In 1954, the Pacific Coast population of trumpeter swans was discovered breeding in Alaska (Hansen et al. 1971). Since 1935, trumpeter swan management has helped restore the species to a nationwide count of 46,225 (SE = 1,172) individuals in 2010 (Groves 2012), but in Wyoming the trumpeter swan is still regarded as an "imperiled" species (Slater 2006) and a "species of greatest conservation need" (WGFD 2011).

Three distinct genetic and geographically separated populations of trumpeter swans are recognized: Pacific Coast, Rocky Mountain, and Interior (Figure 3, Oyler-McCance et al. 2007). The breeding range of the Rocky Mountain Population (RMP) includes the TSF of non-migratory swans in the core Tri-State Region (USFWS 1995)

[A] Appendix A.

and the Canadian Flock (CF) that migrates between the breeding grounds in Canada and the Tri-State Region where the two flocks winter sympatricly (USFWS 2013a).

Growth of the RMP has been mostly attributed to the CF (Figure 4, Proffitt et al. 2009); the 2013 winter survey indicated 90.8% of the RMP were swans from the CF (USFWS 2013a), while the TSF made up just 8.8% with 110 cygnets and 455 adult swans (USFWS 2013b). Abundance estimates of the TSF in YNP range from 59 individuals in 1968 (Proffitt et al. 2009) to 24 swans in the 2013 fall survey (USFWS 2013b). The number of nesting attempts of swans within YNP has decreased dramatically over the last 30 years (Figure 5, McEneaney 2007) with two nesting attempts in 2012 (Smith et al. 2013). Low fledging success rates (cygnets fledged per cygnets hatched) within YNP and surrounding areas, combined with the decline of nesting attempts, have caused the trumpeter swan to be classified as a "species at risk of local impairment" within YNP (McEneaney 2007). The loss of habitat has been loosely linked with local drought conditions (Wyoming Palmer Drought Severity Index [PDSI]; Figure 6, Figure 7, Figure 8). The specific effects of habitat changes on nesting swans has not previously been quantified; an association between drought measures and historical nesting records was analyzed for this study.

Trumpeter swans forage on aquatic vegetation; during the summer in the Greater Yellowstone Ecosystem trumpeter swans primarily foraged on *Potamogeton* spp. (48.2% of fecal composition), *Chara* spp. (14.9%), and *Elodea canadensis* (8.5%; Squires and Anderson 1995). Foraging accounts for 29.6% of the time-budget of wintering swans, but shifts to 44.5% of the time-budget during the spring (Squires and Anderson 1997), and a lack of abundant vegetation may limit nesting swans in YNP, so plant occurrence was measured in historical nesting wetlands.

Past management efforts have included feeding wintering swans and translocation of wintering swans to suitable wetlands, with a focus on expanding the range of the sedentary TSF. During winter, swans are vulnerable to reduced water flows, heavy formations of ice, severe weather, disease, and pollution (Olliff et al. 1999). Translocation efforts were designed to help the TSF by alleviating impacts on resources where swans concentrate, reducing disease transmission, and establishing alternate winter grounds where weather conditions were not as severe (Kilpatrick et al. 2005). These translocation efforts were mostly unsuccessful in achieving the intended objectives. With information derived from GIS modeling; however, habitat use models might be developed to identify suitable sites that are currently unoccupied by trumpeter swans. Flexible mapping programs that incorporate future management goals and that are capable of updating habitat categories based on the latest available imagery are desirable because of their ability to remain effective in future years.

Geographic data have become more precise and readily available in recent years. Geographic Information System (GIS) techniques are well suited to evaluate vegetation and hydrology to identify and monitor potential habitat for trumpeter swans. Landscape changes, such as the 1988 Yellowstone fires or increased human activity near swan nesting ponds, could be factors in the decline of suitable nesting sites and nesting success (Henson and Grant 1991). These changes potentially affect the landscape in a manner that could be assessed when mapped using raster images, GIS software and tools.

As Landsat projects have developed, the accuracy and technology involved in satellite imagery has advanced dramatically. Landsat multi-spectral scanner (MSS) images from the project launched in 1972 (Headley 2010) were processed at 60 m and cover four spectral bands (Table 1[B]). Landsat thematic mapper (TM) images from the project launched in 1978 (Headley 2010) have 30 m resolution with seven total spectral bands (Table 2). The Landsat enhanced thematic mapper plus (ETM+) project was launched in 1999 (Headley 2010) with eight total spectral bands (Table 2). While the resolution of satellite imagery is low compared to that of aerial photography, where resolution is typically between 1 to 2 m, the resolution of 15 to 60 m for satellite images should be sufficient for mapping areas greater than 10 ha. While aerial photographs are sometimes available in a color-infrared format, some aerial photographs are only available in black and white format.

The frequency of Landsat image collection is highly reliable as each satellite has a 16 to 18 day full-Earth coverage cycle (Headley 2010) with 40 years of archived data. Aerial images are available on a five to seven year cycle through the USDA Aerial Photography Field Office with 65 years of archived data. The consistency of the data

[B] Appendix B.

collection makes Landsat images suitable in terms of long-term habitat analysis when the habitat may fluctuate during the season.

Landsat images are ideal for studies where historical data are needed, where the spatial resolution of the data is sufficient to characterize land cover, and where images incorporating several spectral bands may be needed to assess habitat quantity and quality. Furthermore, Landsat data have become more affordable, and computer software capable of processing large amounts of data is readily available (Cowan and Goward 2004). Landsat images and GIS data sources can be used with appropriate software to delineate suitable habitat within a region and to transfer that information onto highly accurate and effective reference maps. Cover vegetation maps have been converted into suitable wildlife habitat maps for grizzly bears (*Ursus arctos horribilis;* Franklin et al. 2002) and Northern Spotted Owls (*Strix occidentalis caurina*; Glenn and Ripple 2004), and for mapping landscape-genetics of Blotched Tiger Salamander sub-populations (*Ambystoma tigrinum melanostictum*; Spear et al. 2005).

Vegetation mapping and wetland modeling require continuous updating due to the dynamic nature of landscapes; fortunately satellite imagery allows for flexible modeling (Maus and Golden 1995). National Wetland Inventory (NWI) data have been compiled into cover maps with limited scope that may be useful in categorizing swan habitat. Aerial photography is considered an accurate method of land cover mapping (Sohl et al. 2004) but transforming the photographs into maps is time-consuming and expensive (Glenn and Ripple 2004), and relying solely on aerial photography is not considered a long-term land cover mapping option (Wright and Gallant 2007). Harvey and Hill (2001) found that the sensitivity of several Landsat bands (from green wavelengths to middle infrared wavelengths) provided more accurate wetland classification than SPOT (Satellite Pour l'Observation de la Terre; Toulouse, France) image data.

Accurate wetland mapping is an important tool used to evaluate land-use, better understand the function of wetlands, and help make management decisions (Baker et al. 2006). Nesting areas used by swans in the Yellowstone Ecosystem are primarily part of wetlands within one of three NWI classifications: palustrine, lacustrine-littoral, and riverine (Cowardin et al. 1979). Following the Cowardin (1979) System, palustrine wetlands include non-tidal wetlands less than 8 ha with the deepest water < 2 m, dominated by vegetation, low salinity, limited by uplands, and traditionally include ponds, marshes, bogs, and swamps. Lacustrine-littoral wetlands occur from the boundary of the shore to a depth of 2 m or to the maximum extent of emergent aquatic vegetation. Riverine wetlands are wetland and deep-water habitats contained by channels with moving water. They are limited by uplands, contain flowing water, but do not include floodplain wetlands. Geography and terrain are key components in creating montane wetlands, as wetlands typically contain poorly drained soils with low slope terrain.

Current management plans focus on monitoring known nesting sites for presence of swans and nesting attempts, and on maintaining quality of breeding wetlands. Management needs include an inventory of habitat characteristics to understand the relationship between trumpeter swan presence and nest site characteristics. Habitat characteristics should be measured at both a landscape and a local wetland scale (Slater 2006). Breeding territories in the YNP generally coincide with an entire nesting lake, and average 10.1 to 15.0 ha in YNP (Olliff et al. 1999), and range from 2.4 to 51.8 ha throughout the entire breeding range (Hansen et al. 1971) with an ideal depth between 30-cm to 90-cm for subsurface foraging (Johnsgard 1978).

This study focused on mapping historic breeding sites within YNP, and was limited to YNP due to the poor success of trumpeter swans nesting there in recent years. The objectives of this study were as follows:

1) Create a map using Landsat imagery of the nesting territories of trumpeter swans in YNP and changes over time;
2) Compare recent Landsat images to historical Landsat images to assess how suitable nesting habitat has changed over time;
3) Identify and predict suitable nesting habitat for trumpeter swans using image classification,
4) Collect selected habitat variables in the field from historical and current nesting territories within YNP to compare habitat characteristics of recently-used sites to those of historical sites no longer used for nesting.

For objective 3, I sought to determine the reflectance characteristics of wetlands known to be used by trumpeter swans, identify habitat shifts that may influence trumpeter swan nesting preference, and identify other locations that have suitable characteristics.

My goal was to produce a habitat model that would assist wildlife managers by identifying potentially suitable wetlands that could be used by breeding trumpeter swans but are not currently part of the monitoring program. By designing the model to be flexible with changes in climate data, and predicted shifts in climate factors, it is possible that the model could indicate areas that are currently unsuitable for trumpeter swan nesting, but could become suitable as climate changes persist.

Swans appear to be sensitive to lead toxicosis (Blus 1994), with lead creating adverse effects on breeding success (Birkhead 1983) as sub-lethal levels of lead result in lower waterfowl survival rates and productivity (Slater 2006). Lead tackle has been banned from use in YNP and the Red Rocks Lake National Wildlife Refuge for several years, but lead tends to stay where deposited and does not deteriorate rapidly in the soil. Lead naturally occurs at low levels in the soil; unique hydrothermal features are known to collect high levels of metals and other potentially toxic compounds (Otton 1997). Lead is easily taken up from the soil by plants and retained in the roots (Sharma and Dubey 2005) or accumulated in leafy matter (Fitzgerald et al. 2003) which may pose a hazard when swans forage on vegetation. As such, an assessment of whether lead was detectable in nesting wetlands was included during sampling and analysis of habitat variables under objective 4.

Anthropogenic disturbances caused by interactions with visitors could impact trumpeter swan nesting; trumpeter swans are known to alter their behavior in response to human disturbance, with pedestrians causing greater disturbance than vehicles (Henson and Grant 1991). Disturbance within 1.0 km of lakes used by swans, including agriculture and forestry practices, can have a significant impact on swan use and these lakes are less likely to be occupied by breeding swans (Banks 1999). These disturbances lead to a risk of nest predation or exposure as eggs might be left uncovered when disturbed. As human visitation increases in YNP (Figure 9), wildlife managers must be prepared to mitigate for unintended impacts that visitors may present, so the potential relationship between visitation rates and trumpeter swans nesting data was evaluated in this study.

CHAPTER 2

STUDY AREA

Research was conducted in YNP, an area established as a National Park in 1872 and preserved by the National Park Service (NPS) under the mission of conserving wilderness and allowing ecosystem processes to naturally occur. YNP encompasses over 8,991 km^2 (2.2 million acres); wetlands total only 10.3% of the area (Elliott and Hektner 2000). Wetlands range in size, depth, and water availability, varying from ephemeral ponds and streams to large, permanent lakes and rivers. The majority of these wetlands are unsuitable for nesting swans due to oligotrophic conditions, fluctuating water levels, and water chemistry influenced from geothermal features (Proffitt et al. 2009).

Nesting territories available in YNP are generally considered 'marginal' as swan nesting habitat because they typically occupy small lakes with forested shorelines, and contain discontinuous feeding and nesting habitat, with a short season for nesting (Proffitt et al. 2009). Elevation ranges from 1,609 m in the northern river drainage to a high of 3,462 m at Eagle Peak. The weather of Yellowstone is long and cold winters with short, cool summers where snowfall accounts for 30% to 70% of annual precipitation (Proffitt et al. 2009).

A total of 46 historical nesting sites were identified in a file provided by the YNP Avian Studies office for this study (L. Baril, pers. comm.). Four sites were located on large bodies of water (e.g., Shoshone Lake) and removed as potential study sites because the exact historical nest location was unavailable and the large size of the lake and deep waters of the lake made transect sampling difficult. Three locations were in remote regions of the park (e.g., Trail Lake) and excluded for logistical reasons. One location was removed due to presence of geothermal features; access to one location was prohibited due to sensitive wildlife; and one location was incorrectly mapped. A total of 36 locations were surveyed, 16 between 6 – 24 July 2009, and 20 between 15 August – 12 September 2010. Field seasons were staggered during summer months to incorporate a range of growing conditions.

CHAPTER 3

FIELD METHODS

Vegetation type and food availability within each nesting location were sampled to compare with Landsat image pixel reflectance to evaluate whether satellite images were useful in estimating these variables. Composition of aquatic vegetation within historic nesting locations was measured through line transect sampling by wading along a 60-m transect and recording vegetation type every 5 m to a maximum depth of 1.2 m. Vegetation was characterized as either emergent or submergent vegetation. Plant samples were collected for verification of genus or species, and destroyed during the identification processes. Line intercept sampling was used and minimal plant samples collected to minimize disturbance to wetland ecosystems, avoiding large plot vegetation removal. Species occurrence and frequency of occurrence were calculated. Plants were identified by using Crow and Hellquist (2000a, 2000b) and Dorn (2001) plant guides.

Weather data during the study was obtained from the nearest weather station, recorded daily by NPS rangers and reported to the National Weather Service (Table 3, NWS 2009; Table 4, NWS 2010). The three-month (June through August), five-month (May through September), and 12-month (July through June) averages of the Wyoming state PDSI, Wyoming Climate Division 1 (Yellowstone River drainage) PDSI, and Wyoming Climate Division 2 (Snake River drainage) PDSI values were obtained from 1931 to 2010 (Wyoming PDSI 2011) and a Pearson product-moment correlation was used to investigate associations with cygnet fledge success, number of territories occupied by pairs, and territories which fledged cygnets according to YNP nesting records.

Water samples were collected in a 500-mL water collection apparatus to determine if patterns existed between water quality and swan presence. Water samples were tested with a Hach Fish and Wildlife Conservation Kit (Model AL-36B; Hach Company, Loveland, CO) within 20 minutes of water collection. Factors sampled were free acidity (gpg $CaCO_3$), alkalinity (gpg $CaCO_3$), carbon dioxide (CO_2), water hardness (gpg $CaCO_3$), dissolved oxygen (mg/L), and pH. Waste water was collected and disposed of to minimize potential for polluting waterways. A HOBO Water Temp Pro v. 2 data logger (Onset Computer Corp; Pocasset, MA) was deployed for a minimum of 10 minutes to measure water temperature (degree C). An independent sample t-test was used to test for a difference in methyl orange alkalinity, carbon dioxide, water hardness, and dissolved oxygen between sites where swans were observed during the study and historical sites from which swans were absent during the study; a Levene's Test for equality of variance was used to indicate if equal variance could be assumed. The pH was broken down into three categories; acidic (pH < 5.5), circumneutral (pH between 5.5 and 7.4), and basic (pH > 7.5) following Cowardin et al. (1979). A Pearson's chi-square test was performed to test if swan presence was independent of the pH of water. Simple linear regression was used to investigate any relationship between water temperature and time of day when sampled, day of year when sampled, territory elevation, or size of foraging zone. Independent sample t-tests were used to test for a difference in elevation, size of foraging zone, and water temperature between sites where swans were observed and historical sites from which swans were absent during the study. Statistical tests were performed using SPSS Student software (PASW version 18.0; IBM Corporation, Armonk, NY).

Lead levels were evaluated in nesting ponds; soil samples were collected along transects to test for the presence of lead in the nesting territory and stored in 59-mL Nalgene specimen vials. Samples were sifted to remove plant matter and rocks and tested for lead using a LeadCheck Soil Test Kit (Catalog #4ST6; Hybrivet Systems, Inc. Framingham, MA), which detects lead levels in the soil at 400 ppm.

CHAPTER 4

LANDSAT/GIS METHODS

Landsat images of the study region were obtained from the Global Observatory for Ecosystem Services website (http://landsat.org; Global Observatory for Ecosystem Services, East Lansing, MI); an image provider with large-scale ortho-rectified Landsat images available for free or purchase. These images were specifically chosen because of the low cost and large area covered compared to private image providers who can charge several hundred dollars for small scale images. The data were available as Landsat MSS data (images taken 10 August 1975 and 3 September 1979), Landsat TM data (14 September 1990), and Landsat ETM+ data (15 September 1999 and 21 July 2005). The MSS data scenes for YNP were found in satellite path 041 and row 029. The TM data and ETM+ data for YNP were found in path 038 and row 029.

The mapping software used was ArcGIS (version 10; Environmental Systems Research Institute, Redlands, CA). Images were clipped to exclude pixels outside the YNP boundary to reduce extraneous data during processing. YNP files were obtained through the NPS Data Store (http://www.nps.gov/gis). NWI maps were overlaid onto the Landsat image and wetlands around the given historical nesting location were categorized into riverine, palustrine, lacustrine-littoral, or lacustrine-limnetic zones. Wetlands within a 5.0 km radius of the nesting area could provide additional food to meet nutritional requirements (Powell and Engelhardt 2000); a maximum 'foraging zone' was calculated using the ArcGIS 'buffer' feature to measure a 5.0 km distance around each nesting lake and using the 'clip' feature to incorporate conterminous wetlands from the NWI file.

Landsat image bands were combined to create a false-color composite image of each year of Landsat data obtained[C]. The bands were combined through the Image Analysis window on-the-fly 'composite bands' function. Pixels from the false-color composite images were placed into a supervised classification using the 'Image Classification' toolbar in ArcGIS. The spectral signature was defined based on the

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[C] Appendix C.

vegetation sampling performed in 2009 and 2010 and was used as the training signature to classify other pixels within wetlands as either 'open water' or 'aquatic vegetation' as identified during plant transect sampling. Pixel classifications were created that identified 'aquatic vegetation' as any pixel where vegetation was present along more than half of the transect line, and 'open water' as pixels where vegetation was absent from more than half of the sampled transect. Aquatic vegetation was combined into 'emergent' and 'submergent' vegetation classifications, and a 'wet meadow' classification was attempted to distinguish areas with shallow water and heavy aquatic vegetation. Other classifications were created to identify areas around wetlands, such as areas burned during the 1988 forest fire and urban settings within YNP. The broadest classifications tested were wetlands identified with swans present versus wetlands identified with swans absent. Finally, image classification was based on NWI wetland maps to see if wetland categories could be distinguished by Image Classification of the Landsat images.

The Normalized Difference Vegetation Index (NDVI) function of Image Analysis is an on-the-fly raster geo-processing option available in ArcGIS that creates a standardized index of vegetation biomass. By using contrasting absorption of red light by chlorophyll and the reflective characteristics of vegetation to infrared light, an NDVI can be processed as a function of the equation: NDVI = [(infrared band – red band) / (infrared band + red band)] and vegetation health may be assessed. The false-color composite image was used to create the on-the-fly NDVI image[D]; when using MSS data, band 2 was input as the red band and band 3 was input as the infrared bad and when using TM or ETM+ data, the red bad was identified as band 3 and the infrared band was identified as band 4. Raw NDVI values were derived using the raster calculator tool. The raw NDVI values generated are between -1.0 and 1.0; where low values or negative values (0.1 and below) correspond to areas with no vegetation (e.g., rock or open water) and high, positive values indicate dense vegetation. Both Landsat composite images and NDVI images were subjectively evaluated for habitat changes over time in an attempt to identify habitat changes which influence swan nesting preference[E].

[D] Appendix D.
[E] Appendix E.

CHAPTER 5

METHODS TO EVALUATE HUMAN-WILDLIFE INTERACTIONS

In order to gain a better understanding of human-wildlife interactions and swan nesting behavior, park visitation records from 1931 to 2011 (NPS 2012) and swan nesting records from 1931-2010 (R. Shea pers. comm.) were compared using a curvilinear regression model to test for a relationship between swan pair occupancy and visitation rates, between number of territories which fledged young and visitation rates, and between cygnets fledged and visitation rates.

Historical nesting territories were categorized as 'near trail' or 'near park highway' or 'remote' by using ArcGIS to locate nesting territories within 1.0 km of a park highway or trail. A chi-square test was used to determine if swan fledging was independent of remote location or accessible locations. A one-way ANOVA was used to test for a difference among near-trail, near-park highway, and remote sites in the number of years when swan pairs occupied sites.

CHAPTER 6

FIELD METHODS RESULTS

Of 86 plant specimens collected, a total of 36 vascular plant species were identified, 6 specimens were identified to genus only, and two specimens were unidentifiable. The 36 species were representative of 20 families, and 27 genera. The five most common plant species found in foraging zones were *Nuphar polysepala* (Yellow pond lily; n = 12), *Schoenoplectus acutus* (Hard-stem bulrush; n = 12), *Stuckenia filiformis* (Fine-leaf pondweed; n =11), *Carex utriculata* (Northwest Territory sedge; n = 11), and *C. aquatilis* (Water sedge; n = 10). These five species made up 29.7% of specimens sampled (Table 5). The five plants with the highest frequency of occurrence along transects were *C. aquatilis* (22%), *N. polysepala* (57%), *Potamogeton natans* (22%), *P. pusillus* (29%), and *S. pectinata* (23%). The family with the largest representation in observed plant samples was Potamogetonaceae with nine species of plants.

Elevation of the nesting territories ranged from 1807 m (Rainbow Lakes) to 2622 m (Crescent Lake) with a mean elevation of 2228 m (Table 6; N = 36; S.D. = 228.6 m). Mean elevation in sites with swans present was 2303 m (n = 11; S.D. = 232 m); mean elevation at sites where swans were absent was 2194 m (n = 25; S.D. = 224 m). Equal variance was assumed; there was no significant difference in an independent sample t-test between elevation in sites where swans were present and sites where swans were absent during the study (d.f. = 34; $t_{crit} = -2.03 > t_{calc} = -1.33$; two-tailed P = 0.19).

By using NWI maps to outline continuous wetland habitat within 5.0 km of the nesting territories, the maximum area of wetlands within foraging zones ranged from 2.0 ha (Slough Creek Ponds) to 2067.6 ha (Bechler Meadows) with a mean of 155.0 ha (Table 6; N = 36; S.D. = 349.4 ha). Of the 36 sites selected, three sites were dry when sampled. Twenty-three sites (64%) were categorized as primarily palustrine, seven sites (19%) were categorized as primarily lacustrine-limnetic, five sites (14%) were categorized as primarily lacustrine-littoral, and one site (3%) was categorized as primarily riverine wetland according to NWI maps (Table 6). The mean area of foraging zone in sites with swans present was 145.6 ha (*N* = 11; S.D. = 144.7 ha); mean area of foraging zone in sites with swans absent was 159.2 ha (*N* = 25; S.D. = 411.4 ha). Equal variance was assumed; there was no significant difference in an independent sample t-test between the area of foraging zone in sites where swans were present and sites where swans were absent during the study (d.f. = 34; $t_{crit} = 2.03 > t_{calc} = 0.11$; two-tailed *P* = 0.92). Within the 5.0 km foraging zones, 18 sites had islands present. Swan presence was independent of the presence of islands within the foraging zone (d.f. = 1; $X^2_{crit} = 3.84 > X^2_{calc} = 1.18$; *P* = 0.28). No cells had an expected count less than 5.

Methyl orange alkalinity was recorded in a range from 1 to 101 gpg $CaCO_3$; the mean alkalinity in sites with swans present was 9.8 gpg $CaCO_3$ (*n* = 11; S.D. = 21.8 gpg $CaCO_3$); mean alkalinity at sites where swans were absent was 10.2 gpg $CaCO_3$ (*n* = 22; S.D. = 20.9 gpg $CaCO_3$). Equal variance was assumed; there was no significant difference in an independent sample t-test between the mean methyl orange alkalinity in sites where swans were present and sites where swans were absent during the study (d.f. = 31; $t_{crit} = 2.04 > t_{calc} = 0.05$; two-tailed *P* = 0.96).

Carbon dioxide was recorded in a range from 0 to 40 mg/L; mean CO_2 in sites with swans present was 6.8 mg/L CO_2 (*n* = 11; S.D. = 5.1 mg/L CO_2); mean CO_2 at sites where swans were absent was 10.7 mg/L CO_2 (*n* = 22; S.D. = 8.5 mg/L CO_2). Equal variance was assumed; there was no significant difference in an independent sample t-test between the mean carbon dioxide in sites where swans were present and sites where swans absent during the study (d.f. = 31; $t_{crit} = 2.04 > t_{calc} = 1.38$; two-tailed *P* = 0.17).

Water hardness was recorded between 1 to 24 gpg $CaCO_3$; mean hardness in sites with swans present was 3.5 gpg $CaCO_3$ (*n* = 11; S.D. = 6.3 gpg $CaCO_3$); mean hardness where swans were absent was 5.2 gpg $CaCO_3$ (*n* = 22; S.D. = 5.4 gpg $CaCO_3$). Equal variance was assumed; there was no significant difference in an independent sample t-test between mean water hardness in sites where swans were present and sites where swans were absent during the study (d.f. = 31; $t_{crit} = 2.04 > t_{calc} = 0.81$; two-tailed *P* = 0.42).

Dissolved oxygen was recorded between 4 to 15 mg/L; mean dissolved oxygen in sites with swans present was 8.1 mg/L (*n* = 11; S.D. = 1.6 mg/L); mean dissolved oxygen at sites where swans were absent was 7.5 mg/L (*n* = 22; S.D. = 2.7 mg/L). Equal variance was assumed; there was no significant difference in an independent sample t-test between the mean dissolved oxygen in sites where swans were present and sites where swans were absent during the study (d.f. = 31; $t_{crit} = 2.04 > t_{calc} = 0.86$; two-tailed $P = 0.40$).

None of the sites were considered acidic (pH < 5.5), 15 sites (45.5%) were considered circumneutral (pH between 5.5 and 7.4), and 18 sites (54.5%) were considered alkaline (pH > 7.4). A Pearson's chi-square test showed swan presence was independent of the pH of water (d.f. = 1; $X^2_{crit} = 3.84 > X^2_{calc} = 0.00$; $P = 1.00$). No cells had an expected count less than 5.

The lowest water temperature recorded was 9.4 C (Beach Springs Lagoon) and the highest water temperature recorded was 25.9 C (Winegar Lake) with a mean temperature of 18.7 C ($n = 33$; S.D. = 4.22). The mean water temperature in sites with swans present was 19.7 C ($n = 11$; S.D. = 4.0 C); the mean water temperature in sites where swans were absent was 18.2 C ($n = 22$; S.D. = 4.3 C). Equal variance was assumed; there was no significant difference in an independent sample t-test between the mean water temperature in sites where swans were present and sites where swans were absent during the study (d.f. = 31; $t_{crit} = 2.04 > t_{calc} = 0.96$; two-tailed $P = 0.35$).

There was a significant linear relationship between water temperature and time-of-day (Figure 10; $R^2 = 0.24$; d.f. = 1, 31; $F_{calc} = 9.82 > F_{crit} = 4.17$; $P = 0.004$). There was a weaker, linear relationship between water temperature and date of sampling (Figure 11; $R^2 = 0.22$; d.f. = 1, 31; $F_{calc} = 8.79 > F_{crit} = 4.17$; $P = 0.006$). There was no significant relationship between water temperature and elevation ($R^2 = 0.09$; d.f. = 1, 31; $F_{crit} = 4.17 > F_{calc} = 3.18$; $P = 0.084$) or water temperature and foraging zone size ($R^2 = 0.02$; d.f. = 1, 31; $F_{crit} = 4.17 > F_{calc} = 0.49$; $P = 0.491$).

Free acidity and phenolphthalein alkalinity were also sampled for each study site with water present, but no statistical analyses were conducted as only two sites registered a reading for free acidity and only four sites registered a phenolphthalein alkalinity reading. A total of 33 soil samples were tested for the presence of lead (samples were not collected in the 3 wetland areas that were dry). None of the samples tested positive for lead levels >400 ppm.

Pearson product-moment correlation was used to investigate if there was an association between three-month (June through August) Wyoming PDSI values and records of cygnets fledged, territories occupied by swan pairs, or number of territories which fledged cygnets. There was no association between the three-month Wyoming state PDSI values and number of cygnets fledged (r = -0.13; d.f. = 78; one-tailed *P* = 0.13) or the three-month Wyoming Climate Division 1 PDSI values and the number of cygnet fledged (r = 0.07; d.f. = 78; one-tailed *P* = 0.28). There was a weak, negative association between the three-month Wyoming Climate Division 2 PDSI values and the number of cygnets fledged (Figure 12; r = -0.22; d.f. = 78; one-tailed *P* = 0.02). There was no association between three-month Wyoming state PDSI values and the number of territories occupied by swan pairs (r = -0.07; d.f. = 78; one-tailed *P* = 0.26), between three-month Wyoming Climate Division 1 PDSI values and the number of territories occupied by swan pairs (r = 0.16; d.f. = 78; one-tailed *P* = 0.08), or between the three-month Wyoming Climate Division 2 PDSI values and the number of territories occupied by swan pairs (r = 0.16; d.f. = 78; one-tailed *P* = 0.08). There was no association between three-month Wyoming state PDSI values and the number of territories which fledged cygnets (r = -0.06; d.f. = 78; one-tailed *P* = 0.30), between Wyoming Climate Division 1 PDSI values and the number of territories which fledged cygnets (r = 0.14.; d.f. = 78; one-tailed *P* = 0.11), or between the three-month Wyoming Climate Division 2 PDSI values and the number of territories which fledged cygnets (r = -0.14; d.f. = 78; one-tailed *P* = 0.11).

Pearson product-moment correlation was used to test for an association between five-month (May through September) Wyoming PDSI values and records of cygnets fledged, territories occupied by swan pairs, or number of territories which fledged cygnets. There was no association between the five-month Wyoming state PDSI values and cygnets fledged (r = -0.13; d.f. = 78; one-tailed *P* = 0.13) or the five-month Wyoming Climate Division 1 PDSI values and cygnets fledged (r = 0.07; d.f. = 78; one-tailed *P* = 0.27). There was a weak, negative association between the five-month Wyoming Climate Division 2 PDSI values and the number of cygnets fledged (Figure 13; r = -0.23; d.f. = 78; one-tailed *P* = 0.02). There was no association between five-month Wyoming state PDSI values and the number of territories occupied by swan pairs (r = -0.07; d.f. = 78; one-tailed *P* = 0.26), the five-month Wyoming Climate Division 1 PDSI values and the number of territories occupied by swan pairs (r = 0.16; d.f. = 78; one-tailed *P* = 0.08), or the five-month Wyoming Climate Division 2 PDSI values and the number of territories occupied by swan pairs (r = -0.10; d.f. = 78; one-tailed *P* = 0.20). There was no association between five-month Wyoming state PDSI values and the number of territories which fledged cygnets (r = -0.06; d.f. = 78; one-tailed *P* = 0.30), the five-month Wyoming Climate Division 1 PDSI values and the number of territories which fledged cygnets (r = 0.14.; d.f. = 78; one-tailed *P* = 0.10), or five-month Wyoming Climate Division 2 PDSI values and the number of territories which fledged cygnets (r = -0.15; d.f. = 78; one-tailed *P* = 0.09).

Pearson product-moment correlation was used to investigate there was an association between twelve-month (July through June) Wyoming PDSI values and records of cygnets fledged, territories occupied by swan pairs, or number of territories which fledged cygnets. There was no association between the twelve-month Wyoming state PDSI values and swans fledged (r = -0.02; d.f. = 78; one-tailed *P* = 0.43), the twelve-month Wyoming Climate Division 1 PDSI values and cygnets fledged (r = 0.15; d.f. = 78; one-tailed *P* = 0.10), or the twelve-month Wyoming Climate Division 2 PDSI values and cygnets fledged (r = -0.11; d.f. = 78; one-tailed *P* = 0.17). There was no association between the twelve-month Wyoming state PDSI values and the number of territories occupied by swan pairs (r = 0.01; d.f. = 78; one-tailed *P* = 0.45) or the twelve-month Wyoming Climate Division 2 PDSI values and the number of territories occupied by swan pairs (r = -0.07; d.f. = 78; one-tailed *P* = 0.27), but there was a weak, positive association between the twelve-month Wyoming Climate Division 1 PDSI values and the number of territories which were occupied by swan pairs (Figure 14; r = 0.25; d.f. = 78; one-tailed *P* = 0.01). There was no association between the twelve-month Wyoming state PDSI values and the number of territories which fledged cygnets (r = -0.03; d.f. = 78; one-tailed *P* = 0.40), the twelve-month Wyoming Climate Division 1 PDSI values and the number of territories which fledged cygnets (r = 0.18; d.f. = 78; one-tailed *P* = 0.06), or the twelve-month Wyoming Climate Division 2 PDSI values the number of territories which fledged cygnets (r = -0.12; d.f. = 78; one-tailed *P* = 0.15).

CHAPTER 7

GIS RESULTS

Multiple vegetation types were often present along transects, and the resolution of each Landsat type (MSS, TM, and ETM+) was too broad to discriminate individual vegetation types. Broad signature classes were created of wetlands identified by swan presence versus swan absence and tested on all NWI wetlands. The broad classification was unable to distinguish differences between specific wetlands where swans were located and those without swans in all Landsat images sampled. The classification signature was refined to define open water (areas identified in plant transects as water with no vegetation visible), aquatic vegetation (areas identified during plant transects as deep water with high amounts of vegetation), and 'wet meadow' habitat (areas identified in plant transects as shallow water with high amounts of vegetation). The resulting classification of the Landsat images frequently over-estimated areas of wet meadow. Various upland habitats were included to refine the classifications, areas with Lodgepole Pine forests and areas of regrowth from the 1988 fires, non-forested sagebrush, thermal areas, and 'urban' settings within the park such as visitor centers. Increasing the number of training samples for the image classification in this manner did not improve the discrimination of spectral reflectance in selected wetlands. Training samples based on NWI wetland maps were unable to distinguish different categories of wetlands.

The NDVI function was used to create a standardized index of vegetation biomass for each wetland sampled. Raw NDVI values were derived using a raster calculator to input the NDVI calculation [(infrared band – red band) / (infrared band + red band)] and the average of the entire foraging zone calculated (Table 7). A curvilinear regression using a quadratic term was chosen because raw data violated the assumptions of linearity in the simple linear regression model; the curvilinear regression was used to test for a relationship between the mean raw NDVI values of located wetlands and pair occupancy and the mean raw NDVI values and fledgling count per wetland. Negative NDVI values indicate areas that lack vegetation, such as bare rock or open water, so these areas were excluded from a second analysis that included only positive NDVI values (Table 8) and pair occupancy, and mean positive NDVI values and fledgling count per wetland. No swans were recorded occupying the sampled wetlands in 1975, therefore the regression analysis was expanded to include a three-year swan analysis which included swan data from the year prior to, and following, image collection. For other image-year comparisons where data were available, analyses were conducted for both the one-year swan data set and three-year swan data set.

For the 1975 image analysis, there was no significant relationship between three-year swan pair occupancy and raw NDVI values ($R^2 = 0.07$; d.f. = 2, 33; $F_{crit} = 3.28 > F_{calc} = 1.15$; $P = 0.33$), three-year swan pair occupancy and positive NDVI values ($R^2 = 0.05$; d.f. = 2, 33; $F_{crit} = 3.28 > F_{calc} = 0.81$; $P = 0.46$), in the three-year dataset of swans fledged and raw NDVI values ($R^2 = 0.05$; d.f. = 2, 33; $F_{crit} = 3.28 > F_{calc} = 0.79$; $P = 0.46$), or the three-year dataset of swans fledged and positive NDVI values ($R^2 = 0.03$; d.f. = 2, 33; $F_{crit} = 3.28 > F_{calc} = 0.58$; $P = 0.57$).

There was no significant relationship in the 1979 NDVI analysis of MSS data between one-year swan pair occupancy and raw NDVI values ($R^2 = 0.02$; d.f. = 2, 35; $F_{crit} = 3.27 > F_{calc} = 0.37$; $P = 0.69$), three-year swan pair occupancy and raw NDVI values ($R^2 = 0.04$; d.f. = 2, 35; $F_{crit} = 3.27 > F_{calc} = 0.67$; $P = 0.52$), one-year swan pair occupancy and positive NDVI values ($R^2 = 0.06$; d.f. = 2, 35; $F_{crit} = 3.27 > F_{calc} = 1.08$; $P = 0.35$), or in three-year swan pair occupancy and positive NDVI values ($R^2 = 0.07$; d.f. = 2, 35; $F_{crit} = 3.27 > F_{calc} = 1.21$; $P = 0.31$). No swans were fledged during 1979, only the three-year dataset of swans fledged and NDVI values were analyzed; there was no significant relationship between three-year swan fledging and raw NDVI values ($R^2 = 0.03$; d.f. = 2, 35; $F_{crit} = 3.27 > F_{calc} = 0.50$; $P = 0.61$) or the three-year swans fledged and positive NDVI values ($R^2 = 0.02$; d.f. = 2, 35; $F_{crit} = 3.27 > F_{calc} = 0.32$; $P = 0.73$).

No significant relationship was found in the 1990 NDVI analysis of TM data between one-year swan pair occupancy and raw NDVI values ($R^2 = 0.11$; d.f. = 2, 35; $F_{crit} = 3.27 > F_{calc} = 2.24$; $P = 0.12$) or three-year swan pair occupancy and raw NDVI values ($R^2 = 0.09$; d.f. = 2, 35; $F_{crit} = 3.27 > F_{calc} = 1.72$; $P = 0.19$). There was a small significant relationship in the one-year swan pair occupancy and positive NDVI values (Figure 15; $R^2 = 0.18$; d.f. = 2, 35; $F_{crit} = 3.27 < F_{calc} = 3.80$; $P = 0.03$) and the three-year swan pair occupancy and positive NDVI values (Figure 16; $R^2 = 0.16$; d.f. = 2, 35; $F_{crit} =$

3.27 > F_{calc} = 3.38; *P* = 0.05); there was no significant relationship between one-year swan fledging and raw NDVI values (R^2 = 0.02; d.f. = 2, 35; F_{crit} = 3.27 > F_{calc} = 0.29; *P* = 0.75) or in the three-year dataset of swans fledged and positive NDVI values (R^2 = 0.00; d.f. = 2, 35; F_{crit} = 3.27 > F_{calc} = 0.03; *P* = 0.97). There was a strong, positive relationship between one-year fledge rate and positive NDVI values (Figure 17; R^2 = 0.38; d.f. = 2, 35; F_{crit} = 3.27 < F_{calc} = 10.54; *P* = 0.001), and no significant relationship between the test of the three-year fledge rate and positive NDVI values (R^2 = 0.11; d.f. = 2, 35; F_{crit} = 3.27 < F_{calc} = 2.28; *P* = 0.12).

There was no significant relationship between the 1999 NDVI analysis of ETM+ data between one-year swan pair occupancy and raw NDVI values (R^2 = 0.05; d.f. = 2, 35; F_{crit} = 3.27 > F_{calc} = 0.94; *P* = 0.40), three-year swan pair occupancy and raw NDVI values (R^2 = 0.03; d.f. = 2, 35; F_{crit} = 3.27 > F_{calc} = 0.61; *P* = 0.55), one-year swan pair occupancy and positive NDVI values (R^2 = 0.07; d.f. = 2, 35; F_{crit} = 3.27 > F_{calc} = 1.25; *P* = 0.30), or the three-year swan pair occupancy and positive NDVI values (R^2 = 0.10; d.f. = 2, 35; F_{crit} = 3.27 > F_{calc} = 1.93; *P* = 0.16). No swans were fledged during 1999, therefore only the three-year dataset of swans fledged was analyzed; there was no significant relationship between the number of swans fledge and raw NDVI values (R^2 = 0.01; d.f. = 2, 35; F_{crit} = 3.27 > F_{calc} = 0.14; *P* = 0.87) or positive NDVI values (R^2 = 0.01; d.f. = 2, 35; F_{crit} = 3.27 > F_{calc} = 0.22; *P* = 0.81).

For the 2005 NDVI analysis of ETM+ data, there was no significant relationship between the one-year swan pair occupancy and raw NDVI values (R^2 = 0.03; d.f. = 2, 35; F_{crit} = 3.27 > F_{calc} = 0.55; *P* = 0.58), three-year swan pair occupancy and the raw NDVI value (R^2 = 0.07; d.f. = 2, 35; F_{crit} = 3.27 > F_{calc} = 1.25; *P* = 0.30), one-year swan pair occupancy and positive NDVI values (R^2 = 0.01; d.f. = 2, 35; F_{crit} = 3.27 > F_{calc} = 0.09; *P* = 0.92), or in the three-year swan pair occupancy and positive NDVI values (R^2 = 0.02; d.f. = 2, 35; F_{crit} = 3.27> F_{calc} = 0.40; *P* = 0.67). The only swan fledged was in 2005, therefore the analysis for one-year and three-year dataset of swans fledged and NDVI values were the same; there was no significant relationship between swans fledged and raw NDVI values (R^2 = 0.01; d.f. = 2, 35; F_{crit} = 3.27 > F_{calc} = 0.24; *P* = 0.79) or positive NDVI values (R^2 = 0.01; d.f. = 2, 35; F_{crit} = 3.27 > F_{calc} = 0.19; *P* = 0.83).

CHAPTER 8

RESULTS OF HUMAN-WILDLIFE INTERACTION EVALUATION

Park records indicated peak park visitation in 2010 with over 3.6 million visitors (Figure 9); while visitation does show fluctuations, a steady trend of increased visitation was observed from 1904 to 2011 (NPS 2012). When using a curvilinear regression model with a quadratic term there was a significant relationship between the number of territories occupied by pairs of swans and park visitation (Figure 18; $R^2 = 0.29$; d.f. = 2, 77; $F_{crit} = 3.12 < F_{calc} = 15.88$; $P < 0.001$); a significant relationship between the number of territories which fledged cygnets and park visitation (Figure 19; $R^2 = 0.37$; d.f. = 2, 77; $F_{crit} = 3.12 < F_{calc} = 22.31$; $P < 0.001$); and a significant relationship between the number of cygnets fledged each year and park visitation (Figure 20; $R^2 = 0.33$; d.f. = 2, 77; $F_{crit} = 3.12 < F_{calc} = 19.32$; $P < 0.001$).

Of 44 trumpeter swan nesting sites, 21 were within 1.0 km of a trail, 12 were within 1.0 km of a main park highway, and 11 were classified as remote. Swan fledging and site location relative to a trail or park highway or remote location were independent (N = 44; d.f. = 2; $X^2_{crit} = 5.99 > X^2_{calc} = 2.24$; $P = 0.33$). All expected cell frequencies were greater than five. The number of years swan pairs occupied the sites was not statistically significant among the three groups (d.f. = 2, 41; $F_{crit} = 3.23 > F_{calc} = 0.16$; $P = 0.85$). The groups were free of outliers, as assessed by inspection of boxplots; the number of years pairs occupied sites was normally distributed among remote sites, trail sites, and park highway sites (Kolmogorov-Smirnov $P \geq 0.14$); variances were equal (Levene's test of homogeneous variance $P = 0.92$).

CHAPTER 9

DISCUSSION

The purpose of this study was to determine if Landsat images were capable of identifying areas of suitable quality for nesting trumpeter swans, based on an analysis of past nesting locations identified in YNP. The goal for this analysis was to provide park managers with a reliable method for assessing habitat quality of nesting wetlands. While the image classification of nesting wetlands was unsuccessful in defining a reflectance characteristic that identifies areas suitable for nesting trumpeter swans, the NDVI classification showed potential for providing information that could contribute to long-term monitoring to address the issues which contribute to trumpeter swan declines. Because declines have led to low pair occupancy rates and fledge rates (Figure 5), all analyses were subject to error due to low sample sizes.

Nesting sites of trumpeter swans in YNP do not generally correspond with wintering areas. Trumpeter swans wintering in YNP are confined to areas of ice-free water, such as the rivers and thermal-fed waters (Banko 1960). Poor wintering range food quality was thought to influence swan reproduction (Squires 1991) and lead to winter supplemental feeding programs, but a more recent study suggested that competition with wintering CF trumpeter swans is not the primary factor in the decline of TSF swans (Proffitt et al. 2009). Swans increase their feeding from 29.6% of their time-budget during the winter to 44.5% of their time during the spring (Squires 1991) and shift dietary needs between winter, spring, and summer (Squires and Anderson 1995). Nesting trumpeter swans of the TSF primarily forage on *Potamogeton* spp. (48.2% of fecal composition). The largest family represented in plant samples during this study was Potamogetonaceae with seven species of *Potamogeton* and two species of *Stuckenia* identified. *Potamogeton* spp. had high frequency of occurrence in samples; *P. natans* (22%), *P. pusillus* (29%), and *S. pectinata* (23%), and were common in wetlands (9 species found across 25 wetlands). These findings indicate that necessary food sources that trumpeter swans require during the nesting season are present in YNP and are not likely to be a limiting factor in the current decline of nesting swans. These findings support the idea that the CF is not depleting resources in YNP prior to the TSF nesting (Proffitt et al. 2009).

There was no significant relationship between the water quality parameters which were sampled and presence or absence of swans during the study, which was comparable to previous work with swans in the region (Squires 1991). These results indicate that the water quality parameters tested were not a contributing factor to whether swans are expected on historical nesting wetlands. None of the sites sampled had a major thermal feature associated with it, although several sites had small thermal features nearby that may have some influence on water chemistry. Lead was not detected in soil samples, although the absence of detectable lead levels does not indicate that lead is entirely absent from the Yellowstone Ecosystem. Lead levels in soil can be unevenly distributed and remain where deposited; any lead pellets or tackle within the park would be expected to be located in the substrate due to the long-standing lead ban. While being trapped in the substrate may limit lead exposure for most animals, swans have a higher encounter risk with lead trapped in the substrate where the roots of aquatic vegetation are growing.

Results indicate that the habitat characteristics which were examined were not significant in influencing the presence or absence of swan pairs on nesting territories in YNP. These results were not expected as swans typically select wetlands for nesting that are between 2.4 to 51.8 ha throughout the breeding range (Hansen et al. 1971) with an ideal depth between 30-cm to 90-cm for subsurface foraging (Johnsgard 1978); several of the locations were larger than would be considered ideal. In this study, methods for calculating nesting territory size utilized NWI maps to derive the area while other studies do not specify the manner which the territory size was calculated.

Drought factors were expected to have a negative impact on trumpeter swan nesting and cygnet fledging as drought might reduce the quality of nesting wetlands by altering the aquatic vegetation composition. Drought factors were quantified by the Wyoming PDSI values (Figure 6, Figure 7, Figure 8) and the association tested between PDSI data and records of cygnets fledged, territories occupied by swan pairs, and number of territories which fledged cygnets. There was a weak, negative association between the June through August Snake River drainage PDSI values and the number of cygnets fledged in YNP (Figure 12), and a slightly stronger, negative association between the number of cygnets fledged and the May through September Snake River drainage PDSI values (Figure 13). These results indicate that the number of cygnets which fledge in the Snake River drainage region of YNP may be impacted during the summer months by changes in seasonal weather patterns. It was expected that drought might have a negative impact on trumpeter swans and fledging rates as young are more vulnerable and food less available when wetlands dry up, an unexpected increase in precipitation can cause nest failure due to flooding. There was a weak, positive association between the July through June Wyoming Yellowstone River drainage PDSI values and the number of territories in YNP which were occupied by swan pairs (Figure 14). These results indicate that a twelve-month drought impact may influence swan pairs choice of specific sites, or impact the selection of new sites in the Yellowstone River drainage area of YNP.

Image Classification was unsuccessful in obtaining a defined pixel characteristic of occupied or historically used nesting wetlands of swans in YNP using MSS, TM, or ETM+ Landsat images. The defined pixel classifications were unable to distinguish aquatic plant species composition, emergent and submergent plant types, open water and aquatic vegetation sites, or define classes based on wetland identification or swan preference. Output of the Image Classification training samples often resulted in an over-estimation of wetland habitat throughout YNP, even after pixel identification was refined by including habitat outside of wetlands in the classification. Refining pixel classification did not resolve the classification outside of the sampled wetlands. Further analysis on fine scale Landsat images was unavailable due to the prohibitive costs associate with high-resolution Landsat data.

NDVI raster calculations provided the average raw NDVI and average positive NDVI values for nesting wetlands; raw NDVI values below 0.1 correspond to areas like rock or open water while high, positive values indicate dense vegetation. The average raw NDVI value (Table 7) and average positive NDVI value (Table 8) for each wetland were compared to swan pair occupancy and fledging records to ascertain whether a relationship existed between NDVI derived values and swan use. Although there was not a significant relationship between NDVI values and swan occupancy or cygnet fledging in most years, some tests did indicate a relationship. There was a statistically significant, but weak, relationship between positive NDVI values from 1990 TM images and the rate of pair occupancy for occupied wetlands in 1990 (Figure 15) and from 1989–1991 (Figure 16). These results indicated that 17.8% of the total variation in swan pair occupancy in 1990 might be explained through factors that are measured in NDVI positive values, and 16.2% of the total variation in swan pair occupancy in 1989–1991 might be explained through positive NDVI values of nesting wetlands. Additionally, there was a strong, positive relationship between the positive NDVI calculated values using 1990 TM images and cygnet fledging rate in 1990 (Figure 17), indicating that 37.6% of the total variation in cygnet fledging in 1990 was explained by the positive NDVI values. As higher NDVI values indicate more vegetation growth, they may indicate better food quality or availability on nesting wetlands. The NDVI model was not reliable in precisely predicting nesting or fledging rates for swans, but the relationships that were significant may indicate that continuous NDVI calculations might assist in remotely monitoring vegetation health in nesting wetlands.

As park visitation has increased in YNP (Figure 9), the evaluation of the human-wildlife dynamic can provide important information to determine if additional protection to sensitive areas is necessary. There was a significant relationship between the number of territories occupied by pairs of swans and park visitation; specifically, 29.2% of the total variation in territory occupancy might be explained by park visitation (Figure 18). Similarly, 36.7% of the variation in whether territories fledged cygnets might be explained by increased visitation (Figure 19) and 33.4% of the variation in the number of cygnets fledged might be explained by park visitation rates (Figure 20). These tests all suggest that the increase of visitors in YNP may influence swan nesting and cygnet fledging within YNP. If vegetation has decreased around nesting sites, it is possible that visitors are more visible to nesting swans, which may lead the swans to be more prone to alter their behavior. A study on swan nesting disturbance indicated that visual obstructions from the highway, such as vegetation or hills, helped to decrease the likelihood of disturbances on the nest (Henson and Grant 1991). Nesting sites such as Trumpeter Lakes and Lake of the Woods are within 1.0 km of a park highway or trail, but the terrain and vegetation make it unlikely that nesting swans will experience high levels of disturbance from stopped vehicles or visitors who are hiking.

Heart Lake, Lewis Lake, and Shoshone Lake were historically productive nesting territories where day use by visitors has potentially impacted swan nesting. All three lakes contain hiking trails, camp sites, recreational boating, and a park highway runs along the shore of Lewis Lake. Swan Lake and Seven-mile Bridge had vehicle pull-outs next to the historical nesting wetland and nature tours are occasionally lead around Swan Lake (R. Shea, pers. comm.); Flat Mountain Arm is considered a 'remote' location due to the lack of trails and roadways, but has back-country campsites accessible by boat. Pedestrian and vehicular traffic, particularly vehicles stopping nearby, can cause nesting swans to alter their behavior (Henson and Grant 1991) and may cause unintentional disturbances on swans. Human-caused disturbances within 1.0 km of lakes used by swans can have a significant impact on swan use, and these lakes are less likely to be used by breeding swans (Banks 1999). Nesting territories identified were referenced in regards to locations within 1.0 km of a trail (n = 21), 1.0 km of a main park highway (n = 12), or remote (n = 11). No statistical significance was found between the visitor accessibility factor and the number of swan pairs which occupied nesting wetlands. Other factors such as the proximity of parking areas to nest territories or visibility of visitor activities from nest territories may be more important factors and were not evaluated with this test. Park managers must carefully gage the impacts that visitation may have on sensitive wildlife in order to adequately mitigate these issues.

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APPENDIX A:
FIGURES

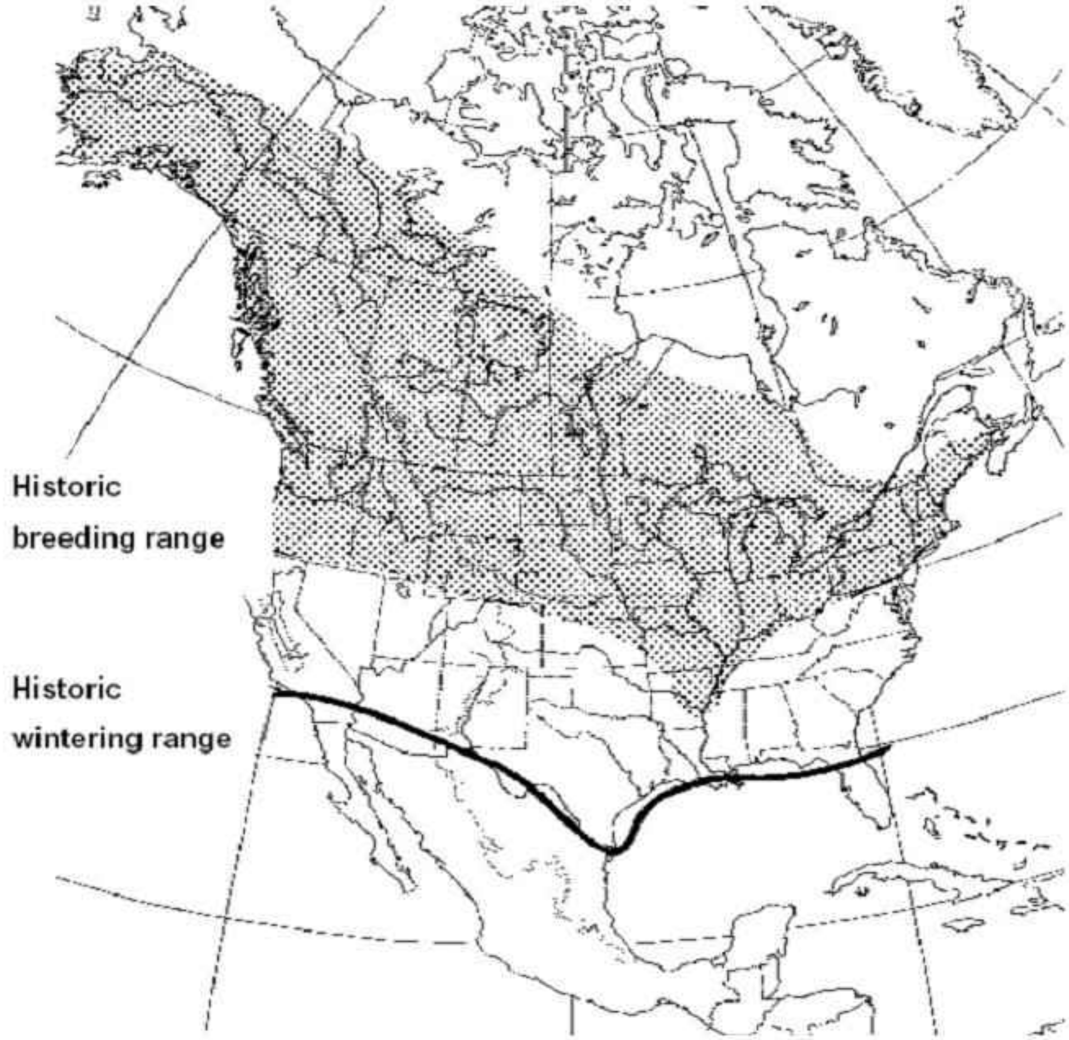

Figure 1. Historical breeding and wintering range of trumpeter swans (*Source:* Matteson, S., S. Craven, and D. Compton. 1995. The trumpeter swan. Publication no. G3647. University of Wisconsin–Extension, Madison, WI.).

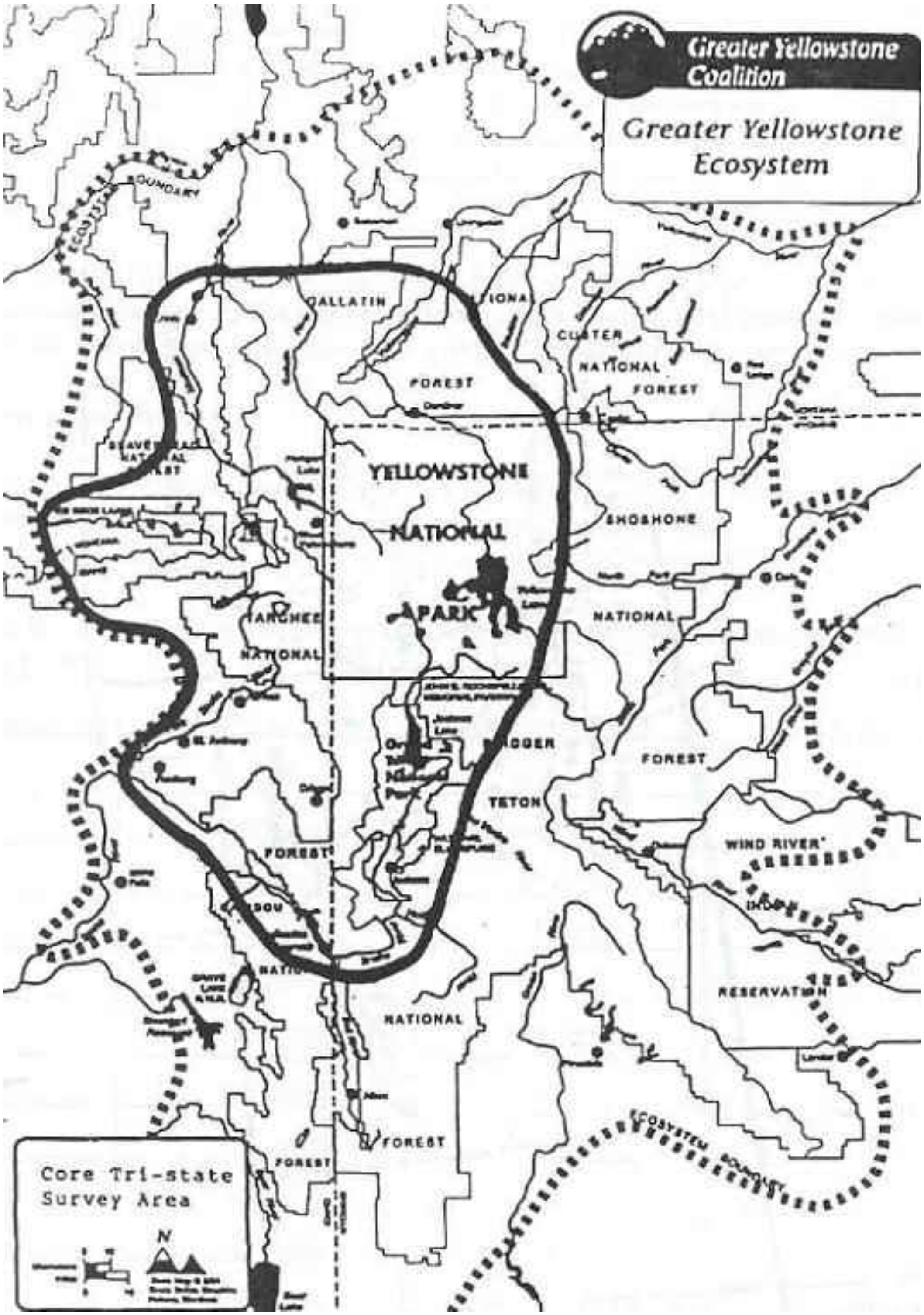

Figure 2. Greater Yellowstone Ecosystem Core Region (*Source:* USFWS. 2006. Trumpeter swan survey of the Rocky Mountain Population – winter 2006. U. S. Fish and Wildlife Service, Migratory Birds and State Programs, Lakewood, CO.).

Figure 3. Geographical distribution of the trumpeter swan (*Source:* Caithamer, D.F. 2001. Trumpeter Swan Population Status, 2000. Division of Migratory Bird Management, U.S. Fish & Wildlife Service, MD.).

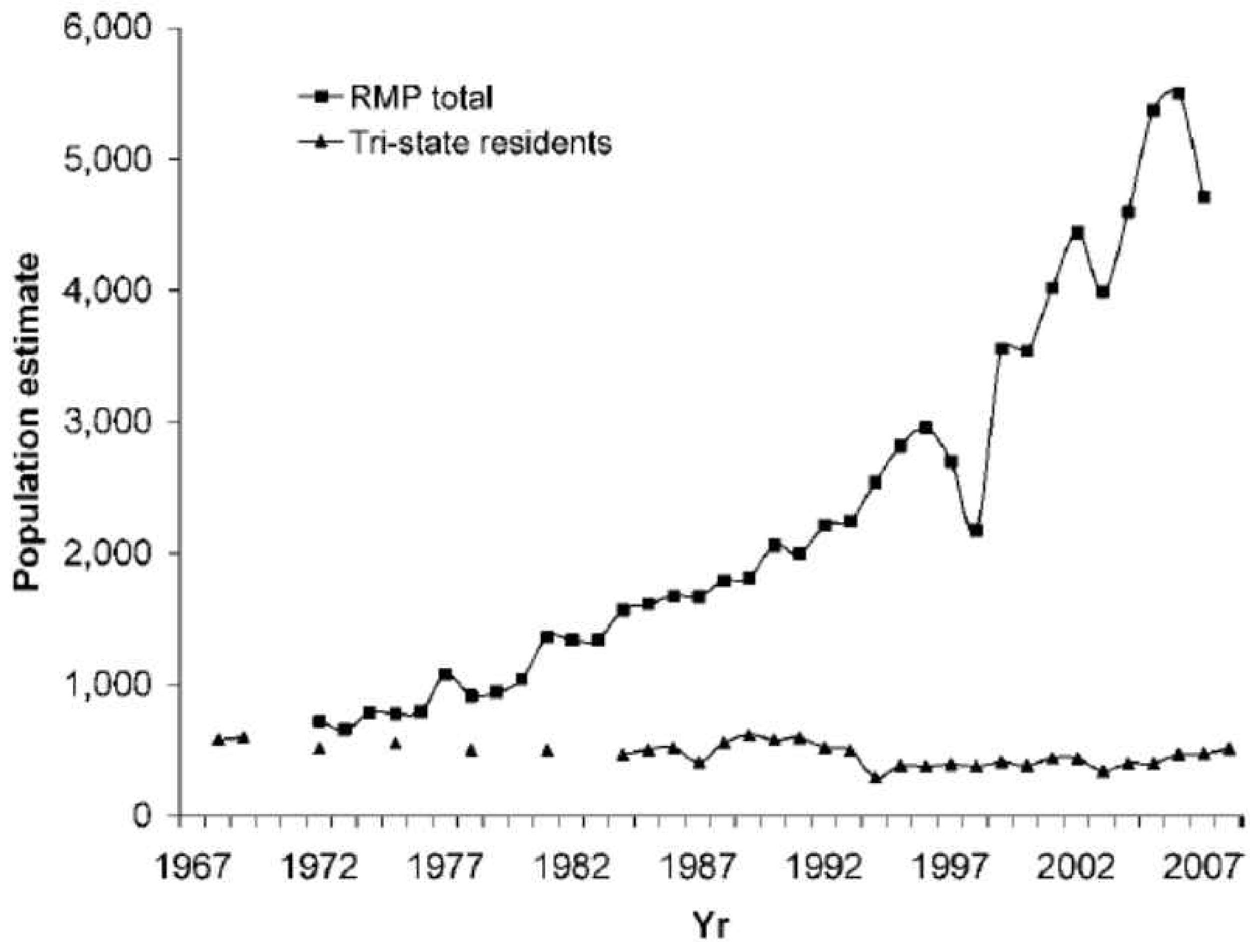

Figure 4. Population estimates of the Rocky Mountain Population of trumpeter swans and the tri-state flock growth from 1971 to 2007 (*Source:* Proffitt, K.M., T.P. McEneaney, P.J. White, and R.A. Garrott. 2009. Trumpeter Swan Abundance and Growth Rates in Yellowstone National Park. Journal of Wildlife Management 73:728-736).

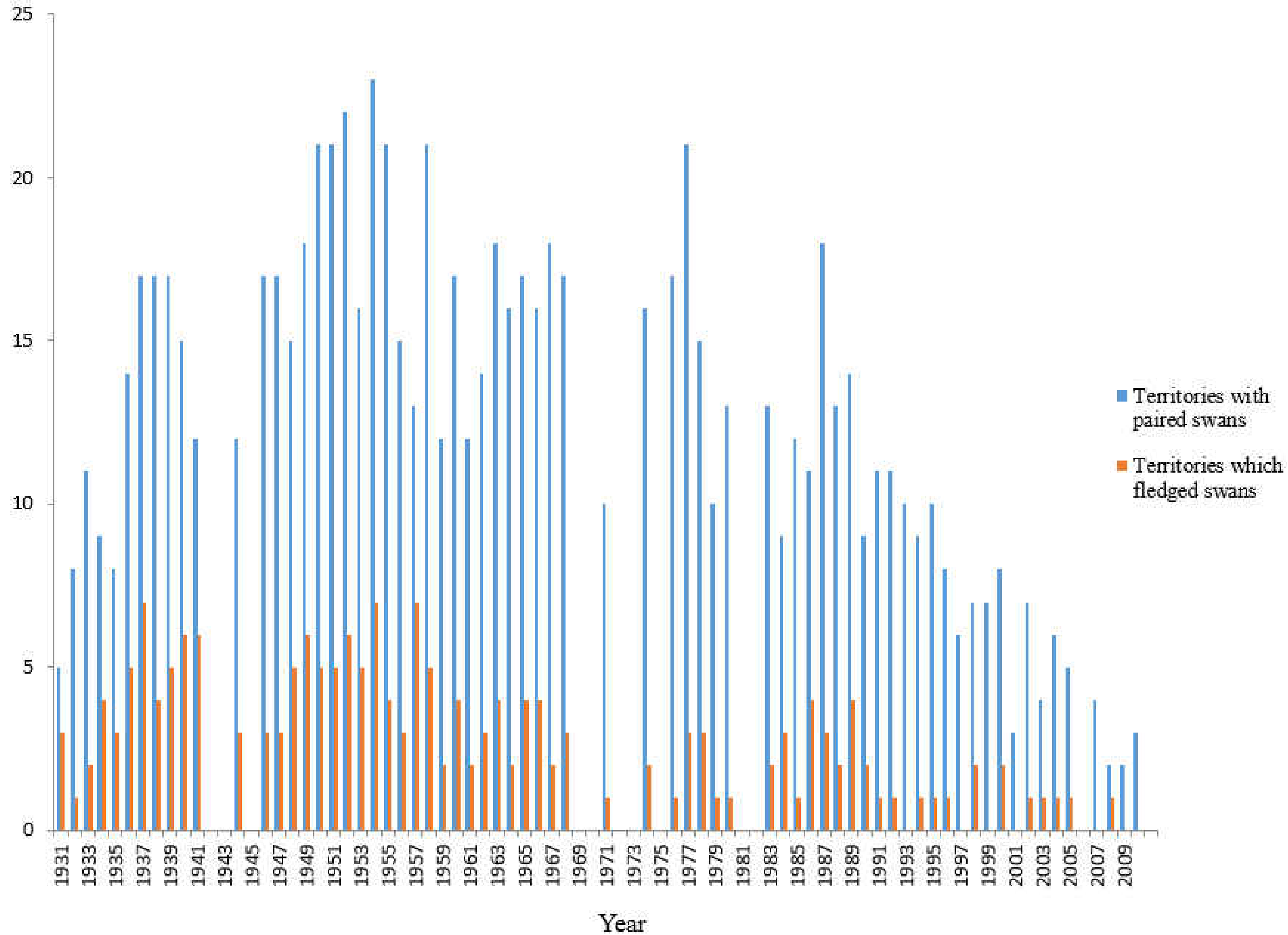

Figure 5. Territory occupancy by swan pairs and territories which fledged swans; Yellowstone National Park 1931 to 2010.

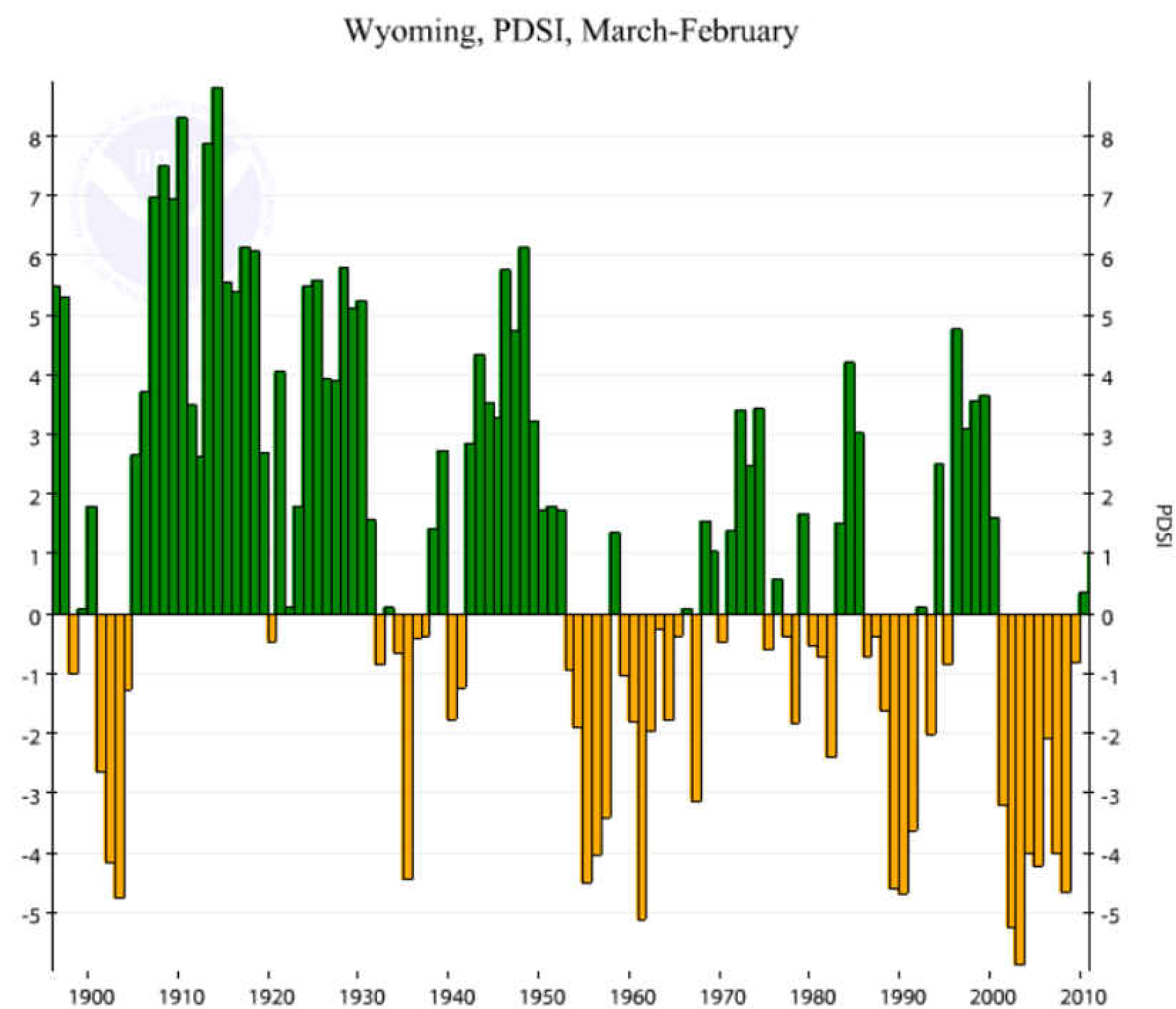

Figure 6. Palmer Drought Severity Index for Wyoming state, March 1896 to February 2011 (*Source:* Wyoming PDSI. 1896 to 2011. [http://www.ncdc.noaa.gov/cag/time-series/us]. Accessed 21 March 2011.).

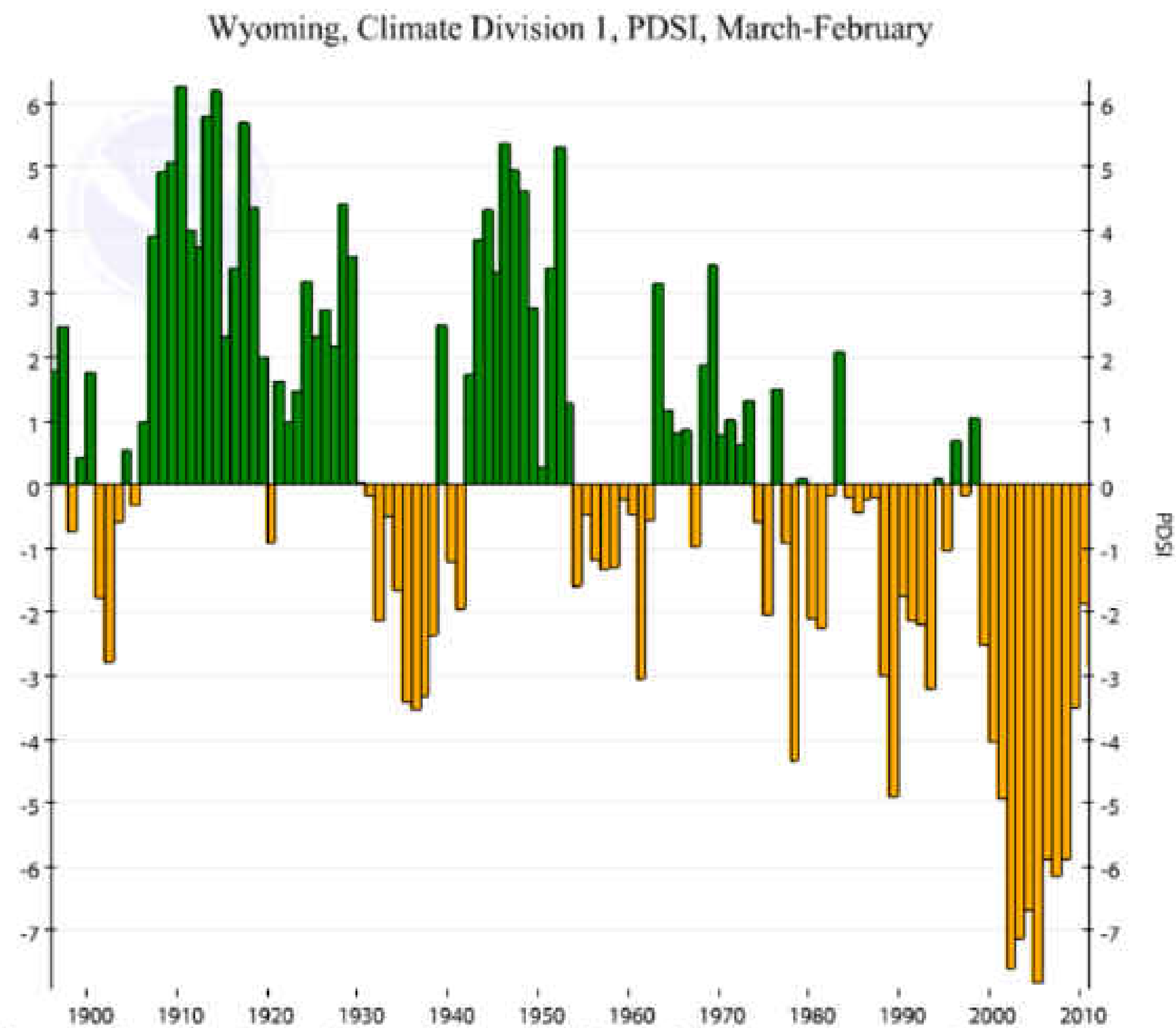

Figure 7. Palmer Drought Severity Index for Wyoming Climate Division 1, March 1896 to February 2011 (*Source:* Wyoming PDSI. 1896 to 2011. [http://www.ncdc.noaa.gov/cag/time-series/us]. Accessed 21 March 2011.).

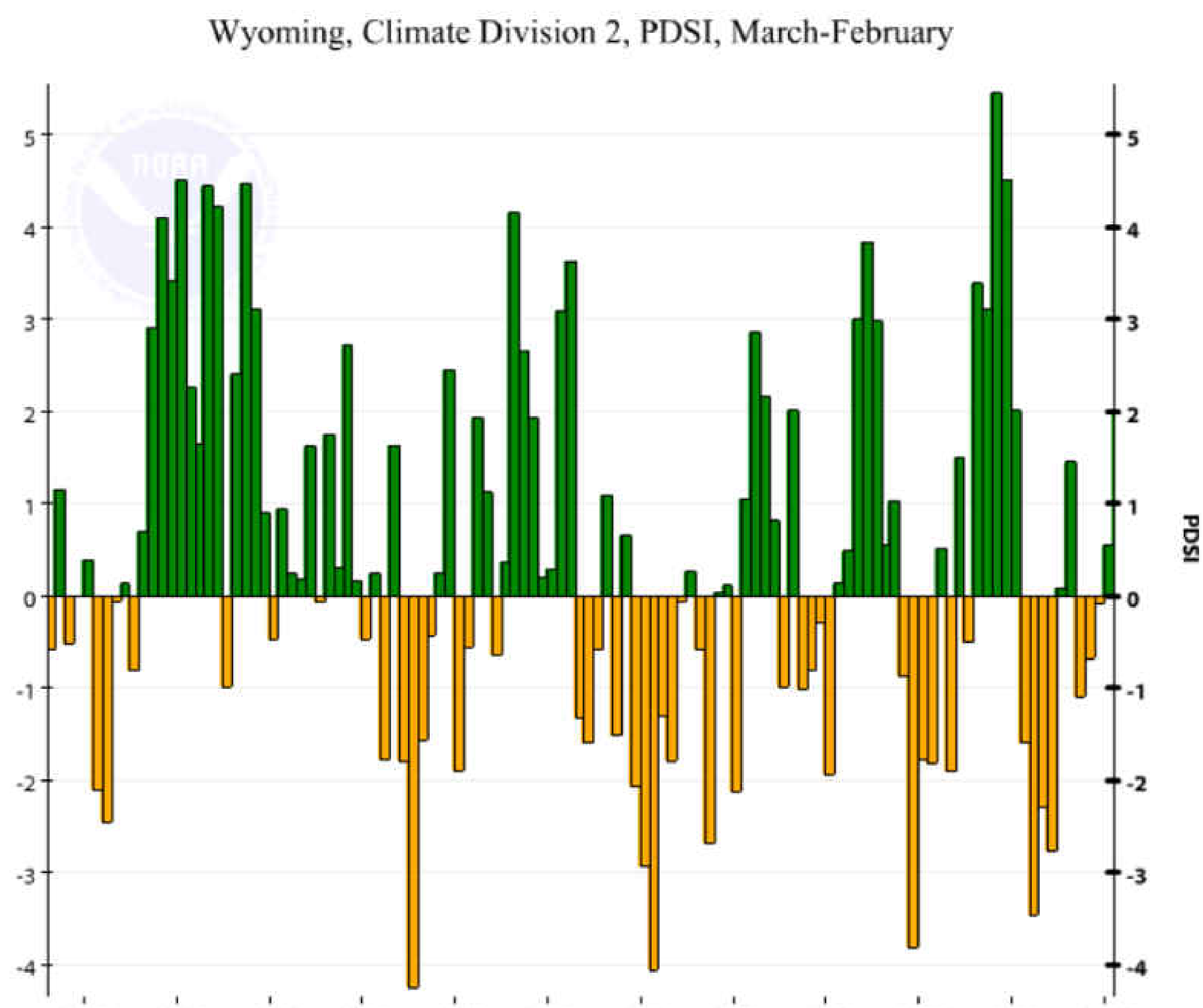

Figure 8. Palmer Drought Severity Index for Wyoming Climate Division 2, March 1896 to February 2011 (Wyoming PDSI. 1896 to 2011. [http://www.ncdc.noaa.gov/cag/time-series/us]. Accessed 21 March 2011.).

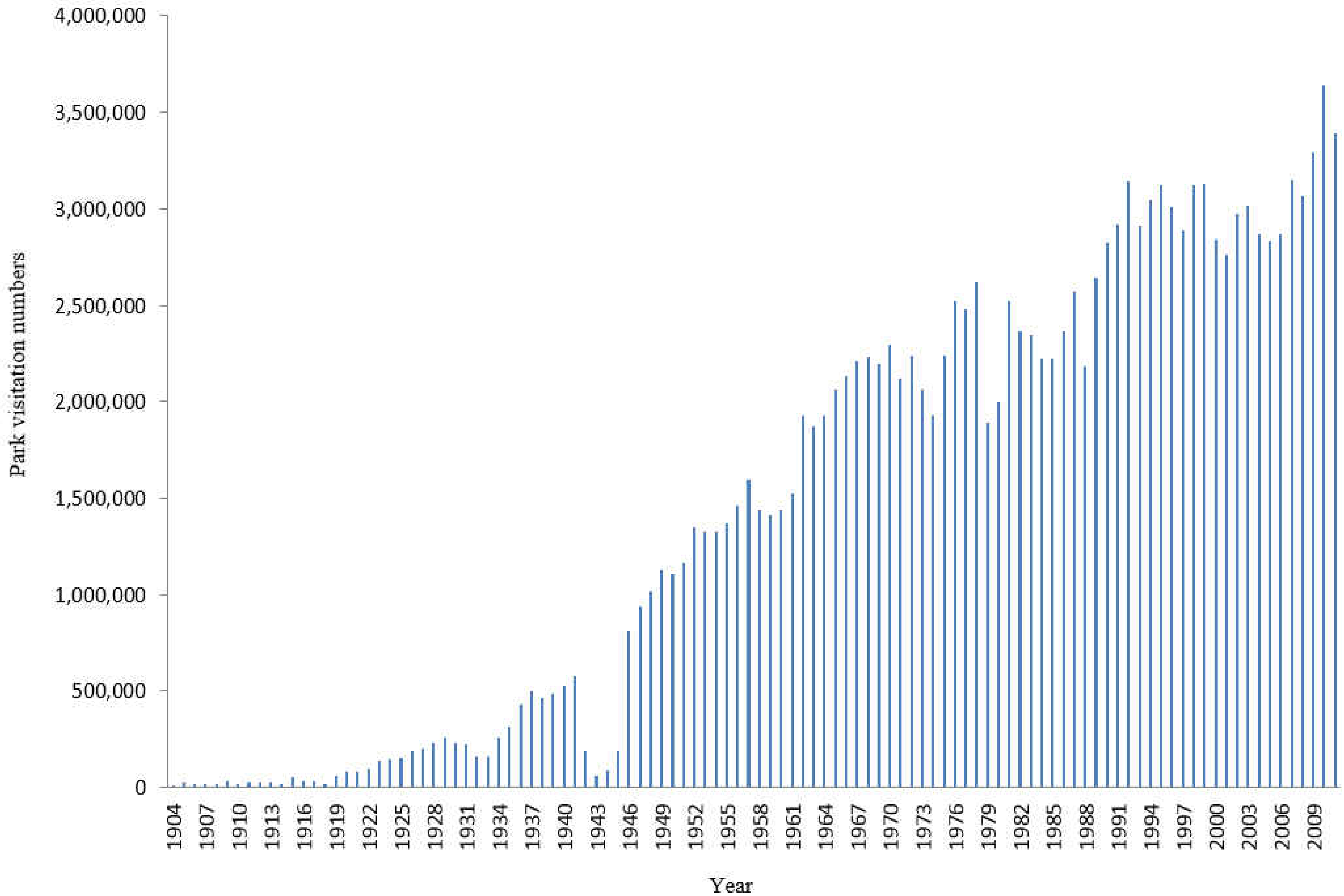

Figure 9. Yellowstone National Park annual visitation records from 1904 to 2011.

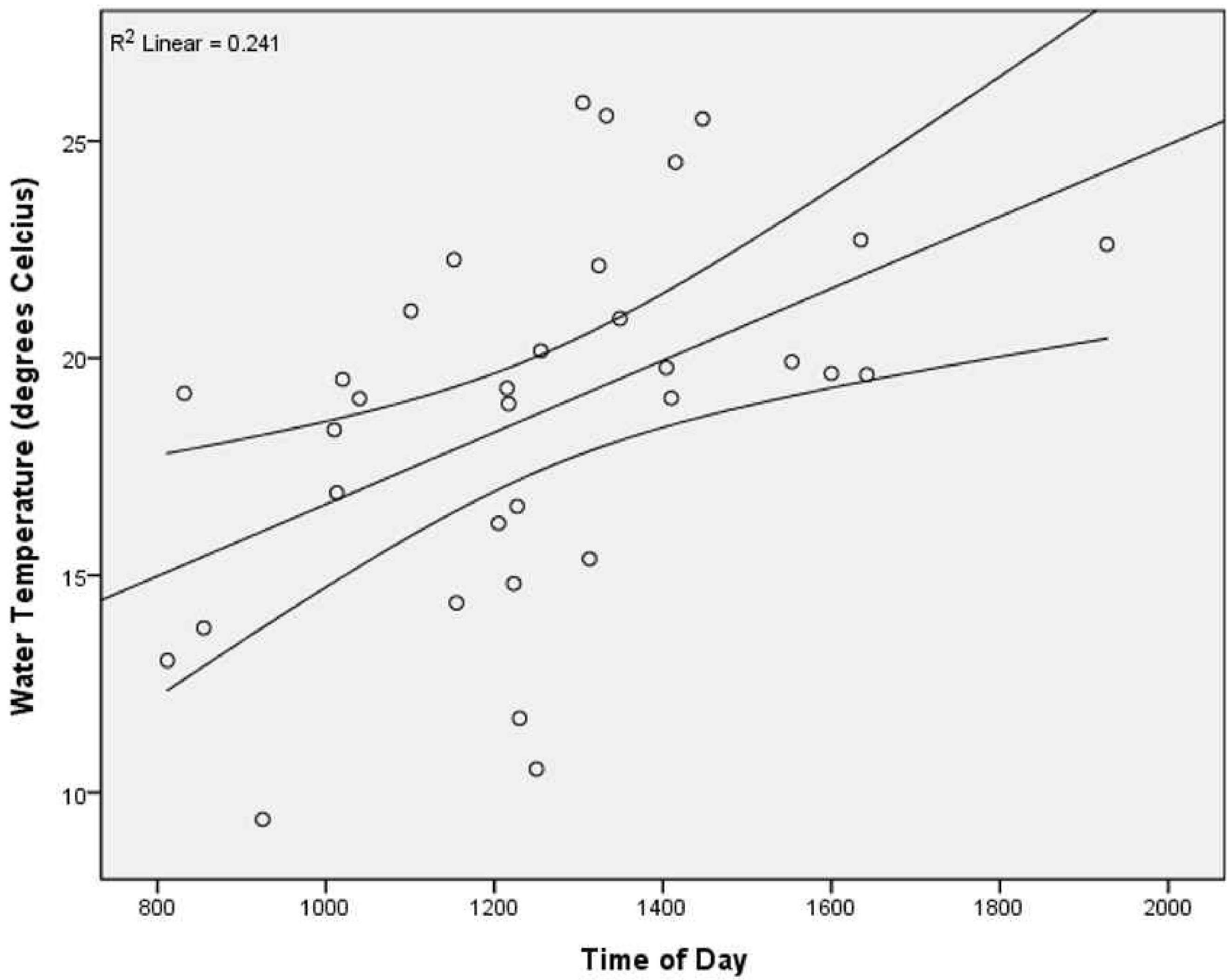

Figure 10. Simple scatter plot with simple linear regression model of water temperature and time of day when sampling occurred ($\hat{Y} = 0.008x + 8.358$; $P = 0.004$) with 95% confidence intervals.

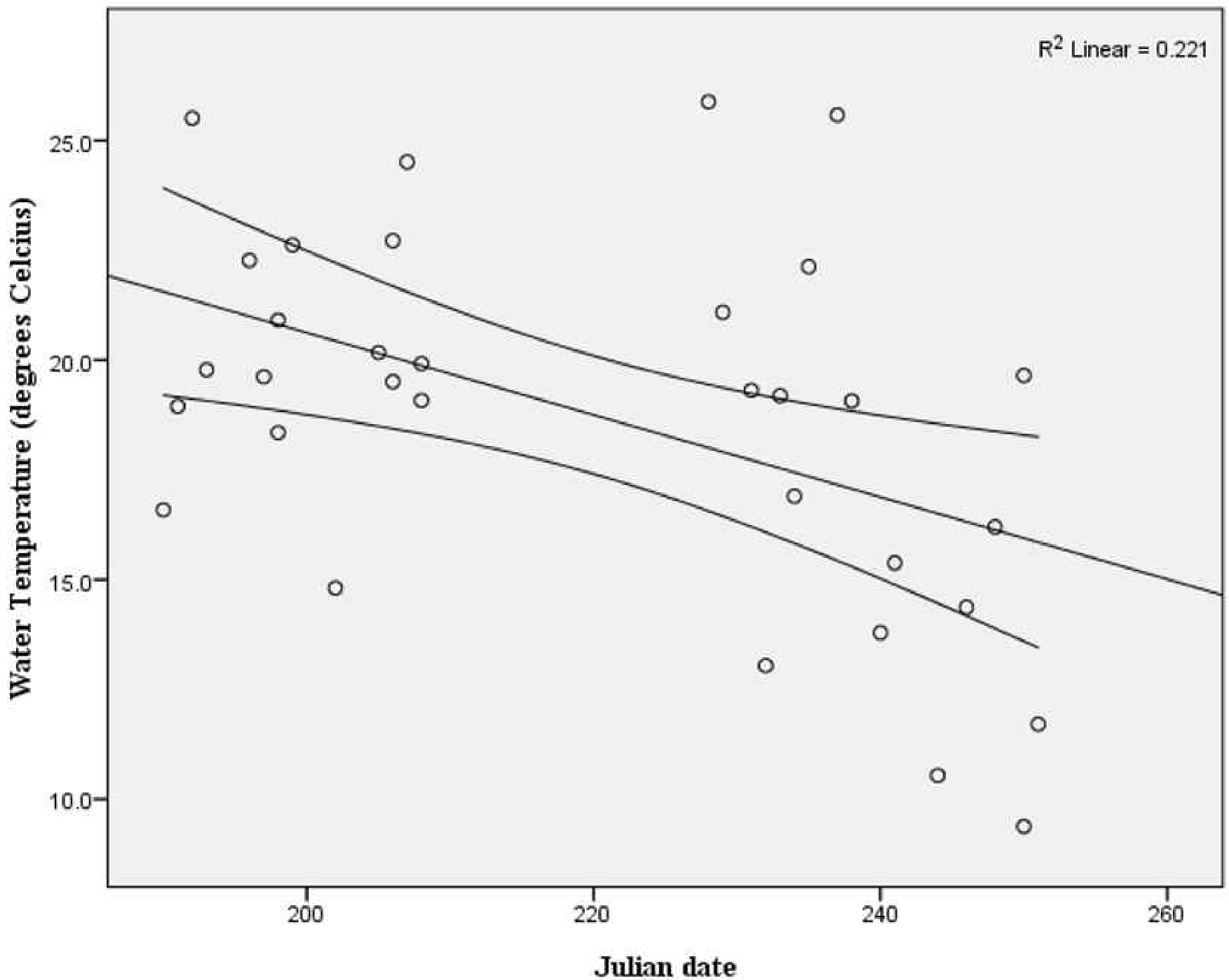

Figure 11. Simple scatter plot with simple linear regression model of water temperature and Julian date when sampling occurred ($\hat{Y} = -0.094x + 39.33$; $P = 0.006$) with 95% confidence intervals.

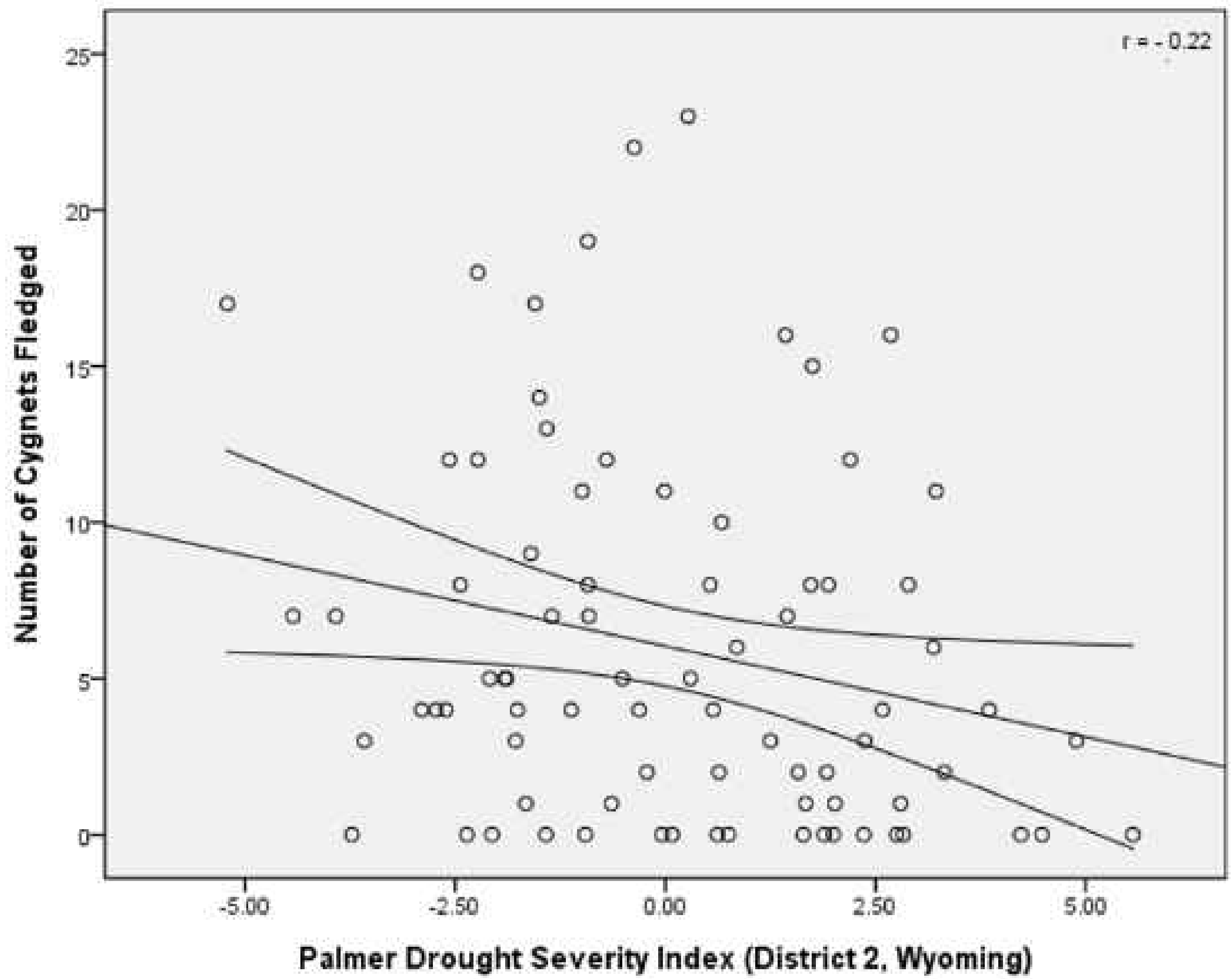

Figure 12. Simple scatter plot with Pearson product-moment correlation showing association of cygnets fledged and the three-month Wyoming District 2 PDSI from 1931 to 2010 ($P = 0.02$).

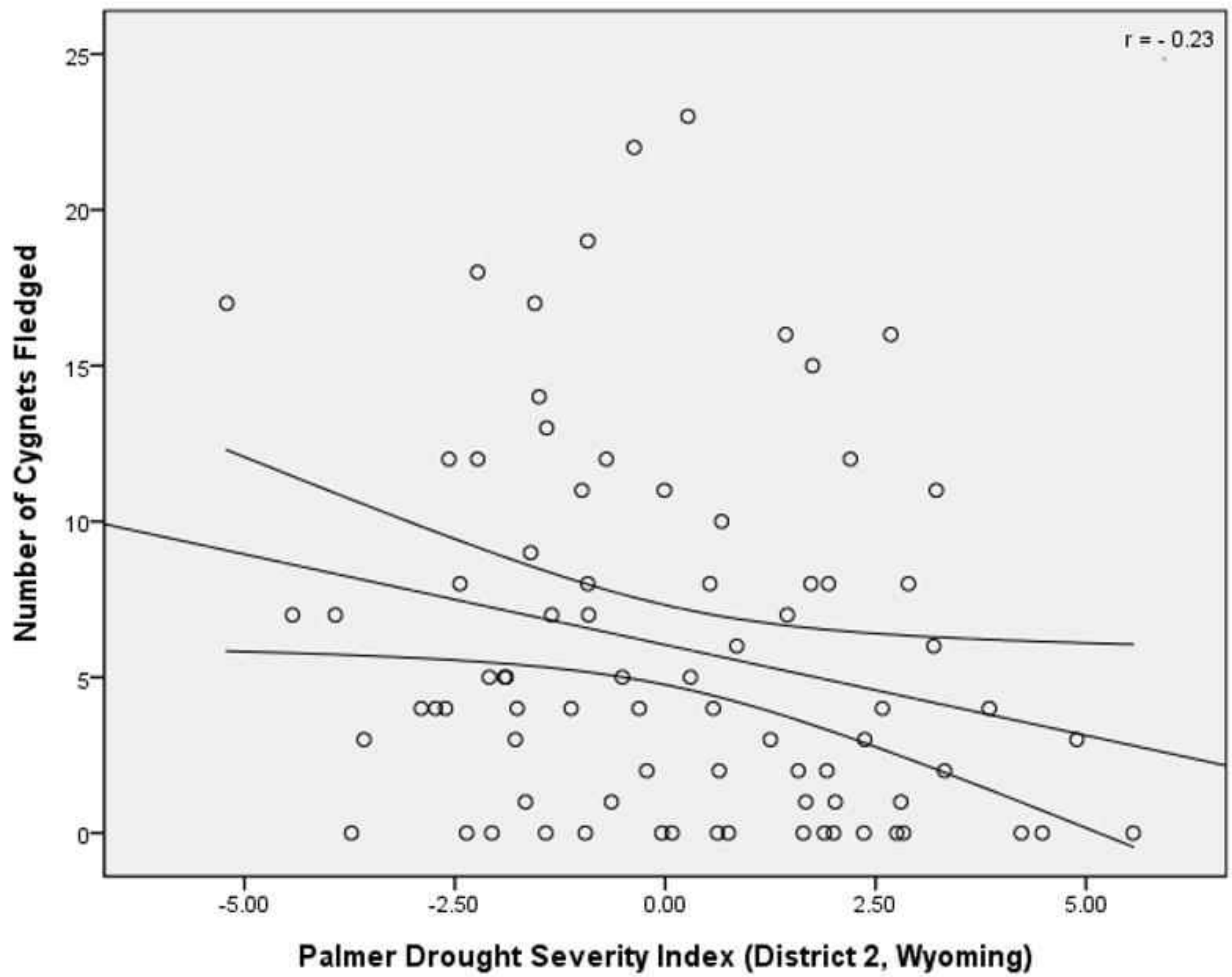

Figure 13. Simple scatter plot with Pearson product-moment correlation showing association of cygnets fledged and the five-month Wyoming District 2 PDSI from 1931 to 2010 ($P = 0.02$).

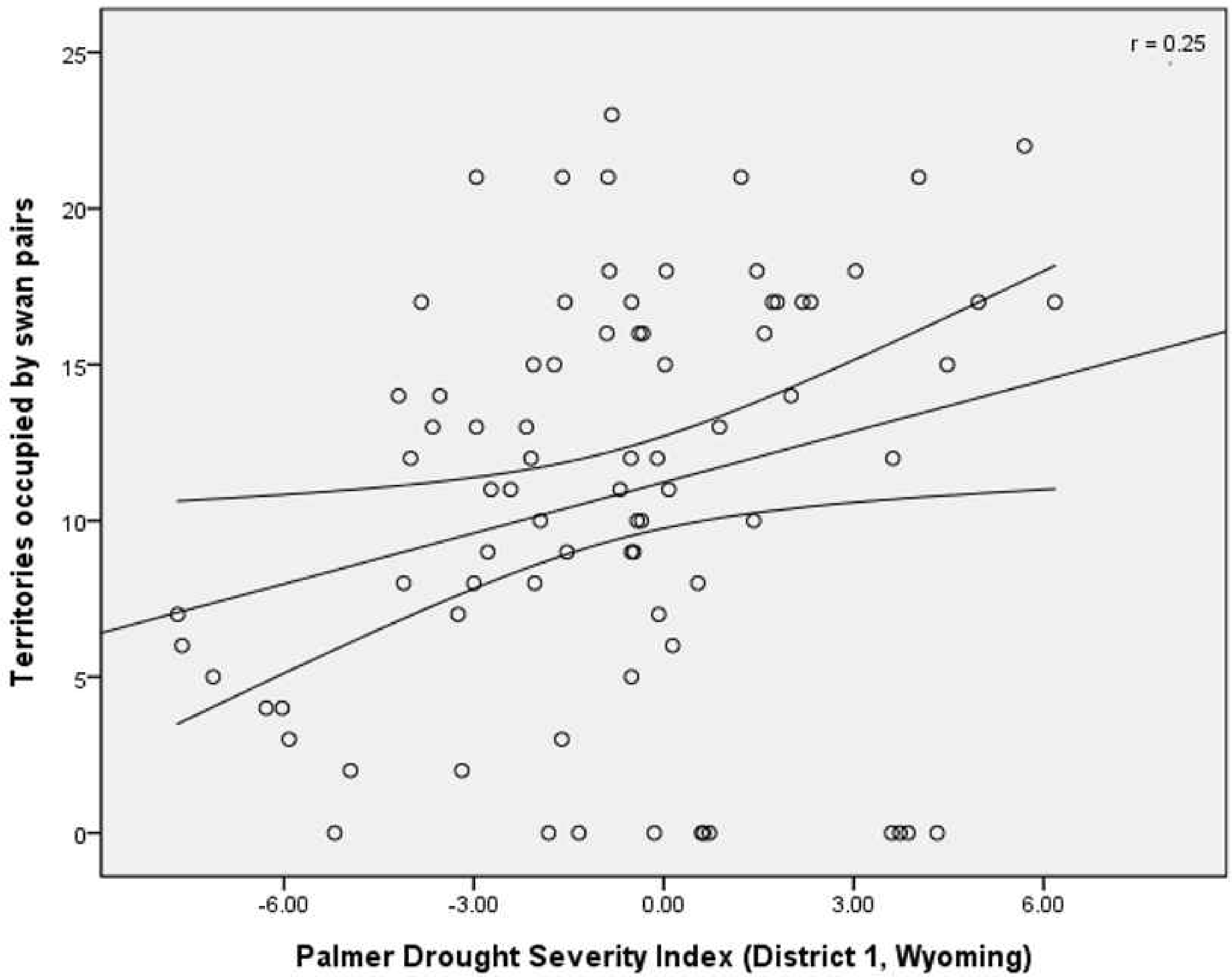

Figure 14. Simple scatter plot with Pearson product-moment correlation showing association of territories occupied by swan pairs and the twelve-month Wyoming District 1 PDSI from 1931 to 2010 ($P = 0.01$).

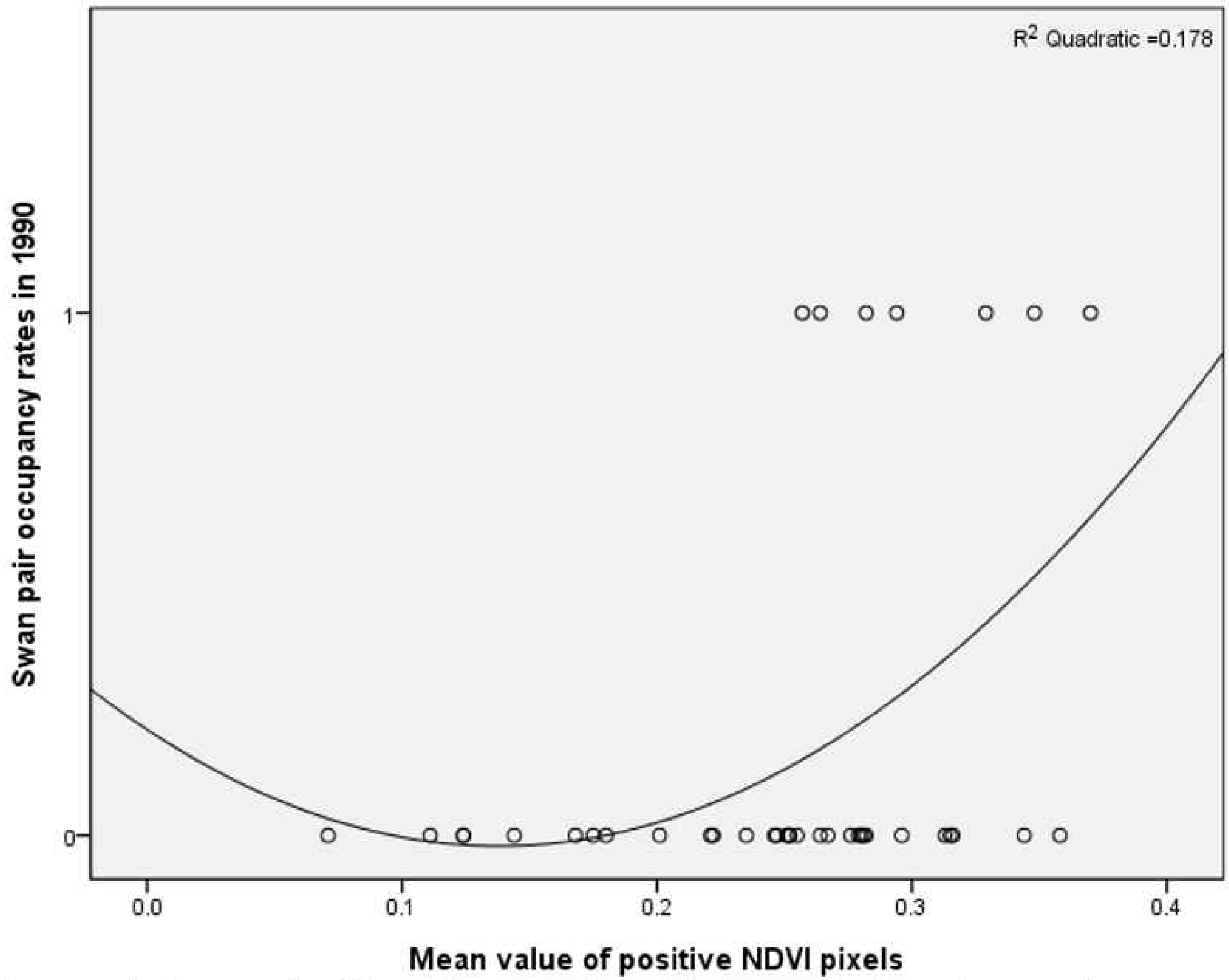

Figure 15. Simple scatter plot with curvilinear regression model using a quadratic term for swan pair occupancy rates in 1990 and the positive NDVI values calculated from 1990 TM Landsat images ($P = 0.03$).

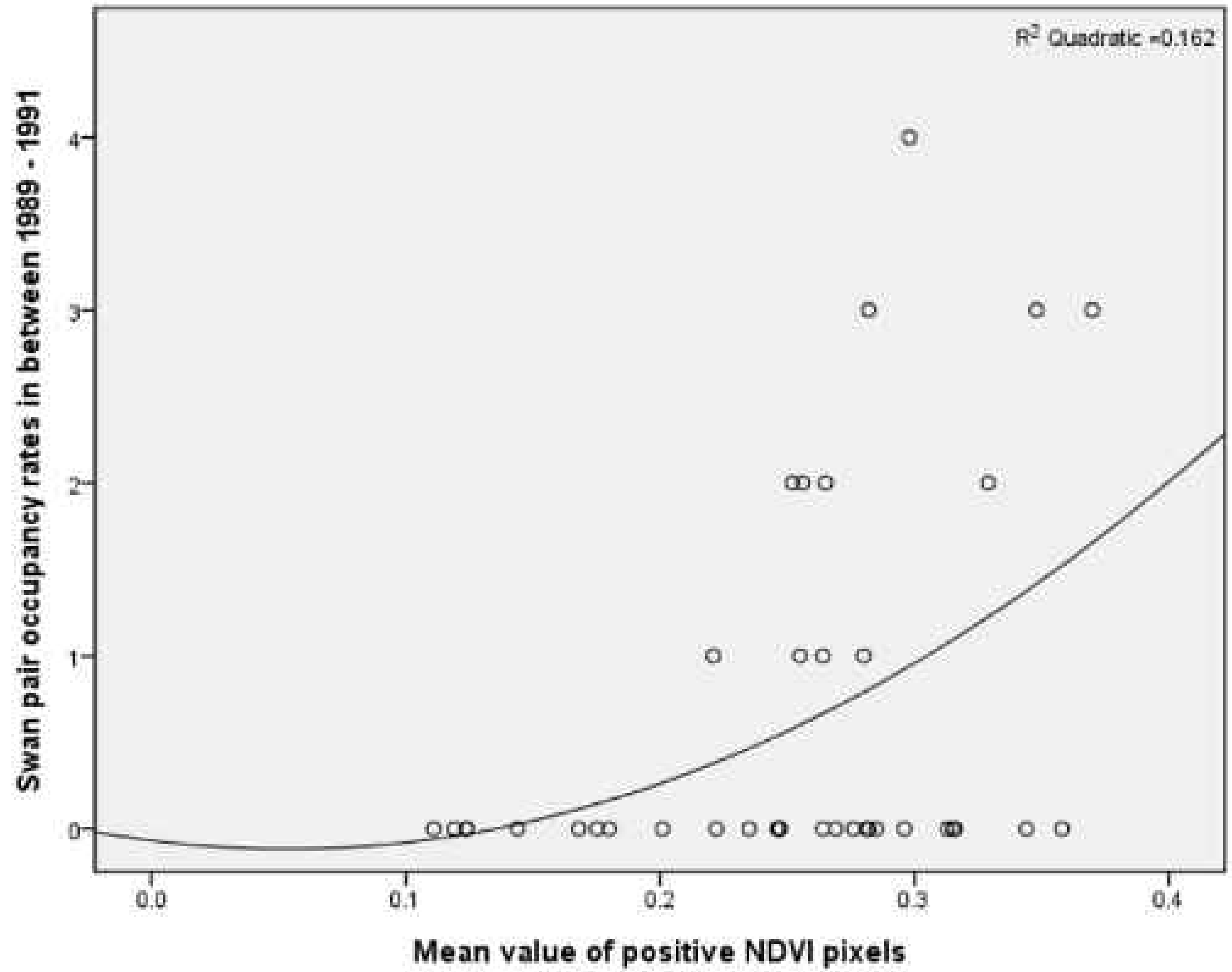

Figure 16. Simple scatter plot with curvilinear regression model using a quadratic term for swan pair occupancy between 1989 – 1991 and the positive NDVI values calculated from 1990 TM Landsat images ($P = 0.05$).

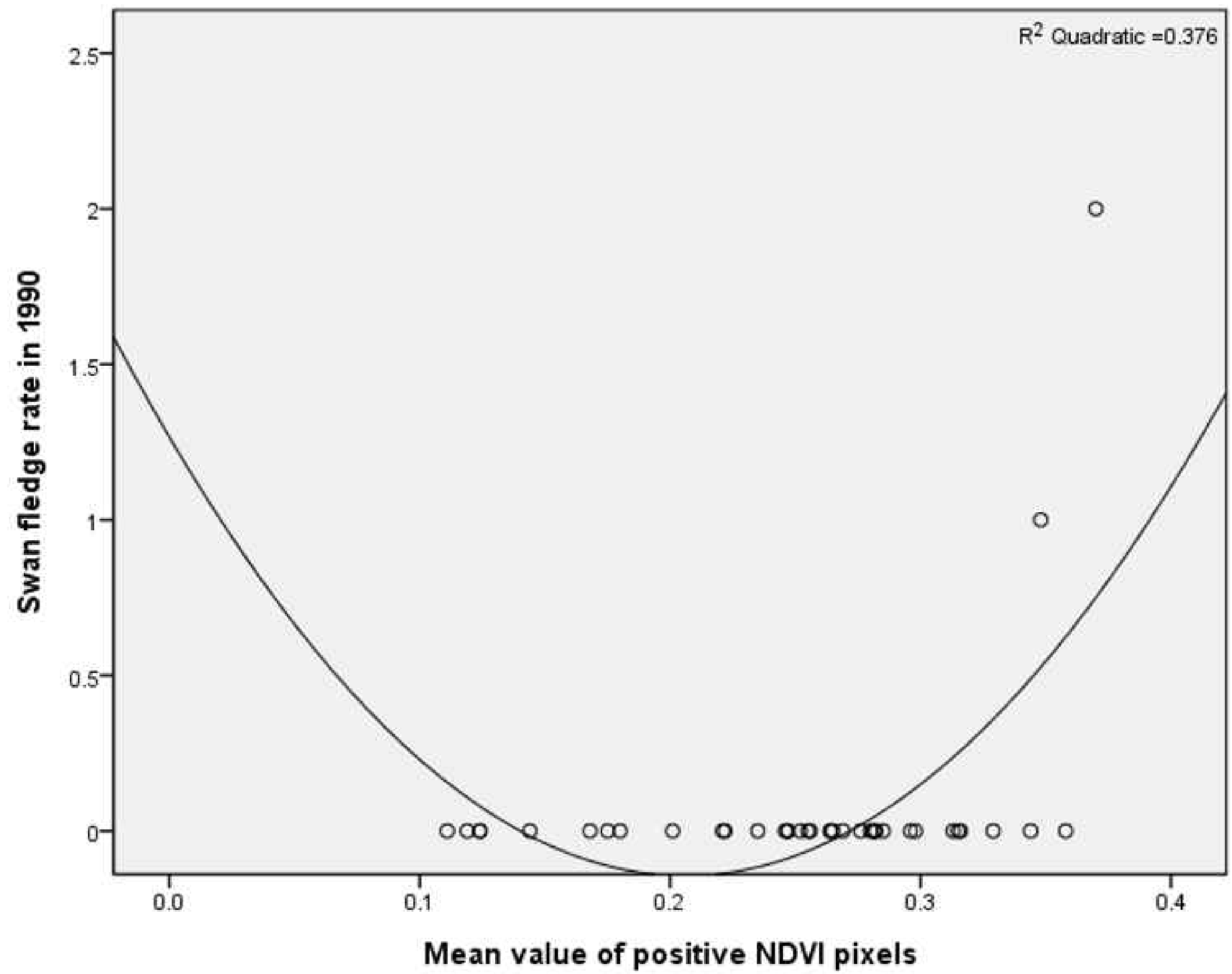

Figure 17. Simple scatter plot with curvilinear regression model using a quadratic term for swan fledge rate in 1990 and the positive NDVI values calculated from 1990 TM Landsat images ($P < 0.001$).

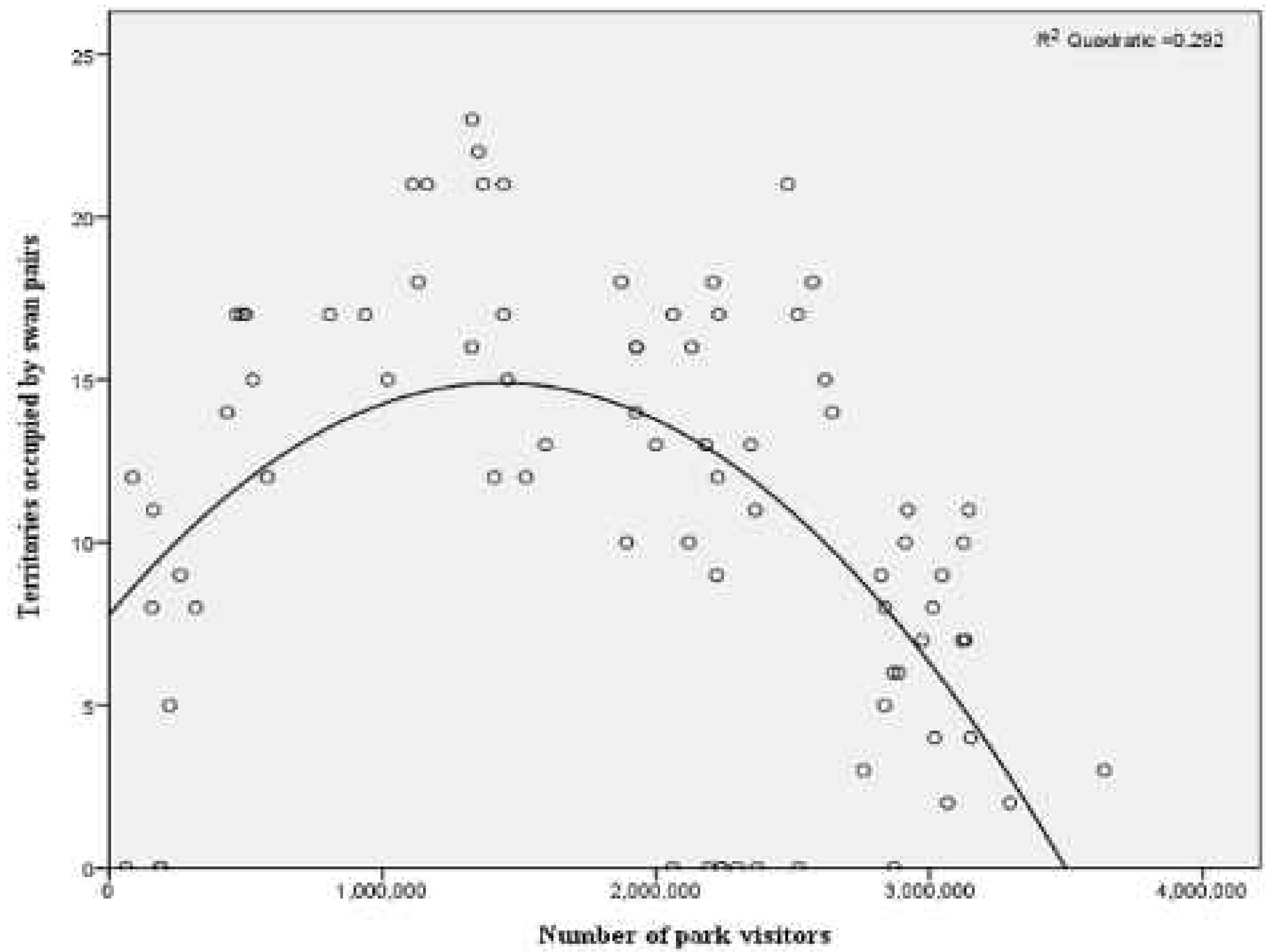

Figure 18. Simple scatter plot with a quadratic regression model based on park records of territories occupied by swan pairs and park visitation records from 1931 to 2010 ($P < 0.001$).

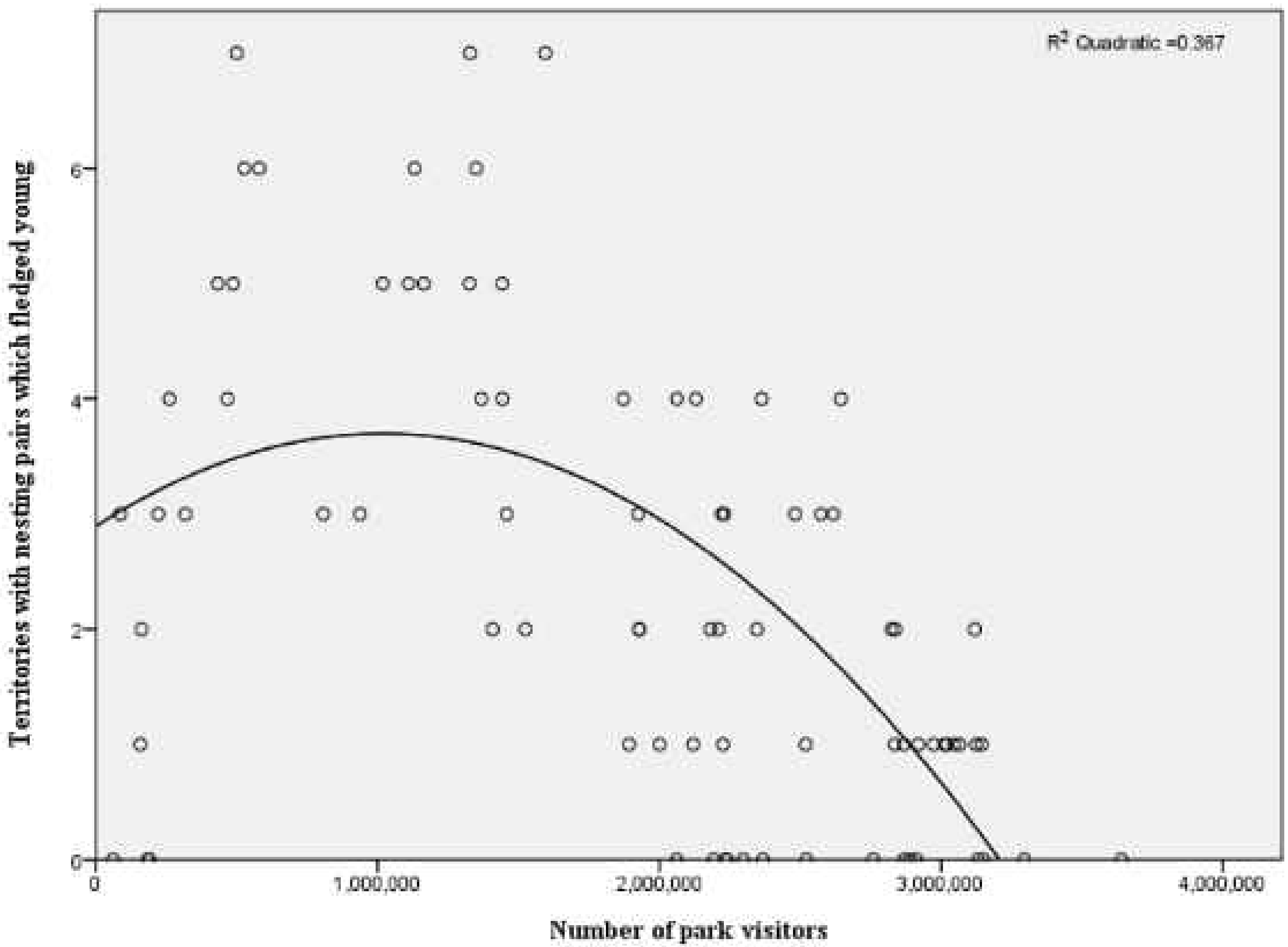

Figure 19. Simple scatter plot with a quadratic regression model based on park records of occupied territories which fledged young and park visitation records from 1931 to 2010 ($P < 0.001$).

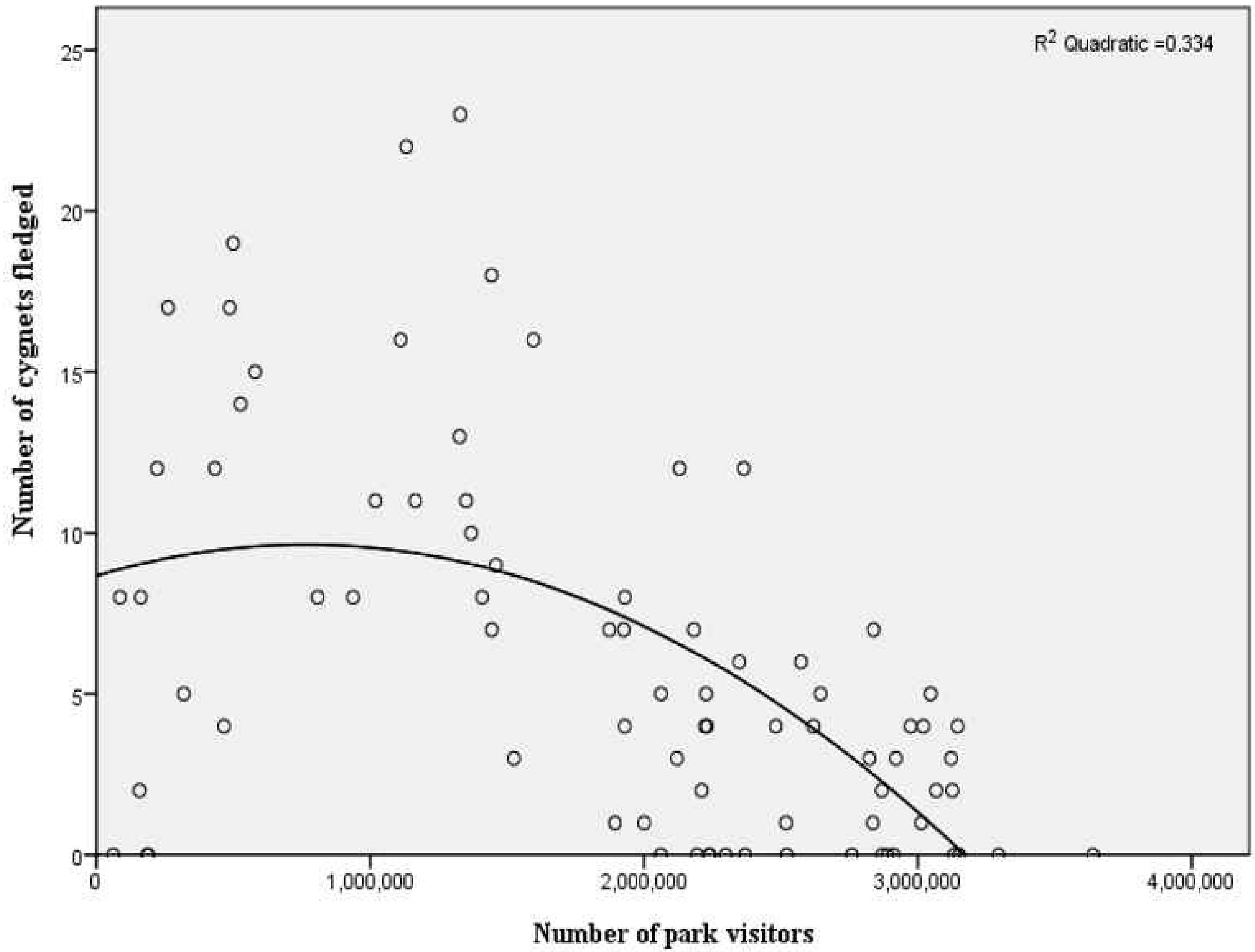

Figure 20. Simple scatter plot with a quadratic regression model based on park records of fledged cygnets and park visitation records from 1931 to 2010 ($P < 0.001$).

APPENDIX B:
TABLES

Table 1. Spectral band function for MSS Landsat missions 4/5 (*Source:* Headley, R. 2010. Landsat: A global land-imaging project. U.S. Geological Survey Fact Sheet 2010–3026.).

Spectral Band	Wavelength (nm)	Use for mapping:
Band 1 – Green	0.5 – 0.6	Sediment-laden water; delineates areas of shallow water.
Band 2 – Red	0.6 – 0.7	Cultural features.
Band 3 – Near Infrared	0.7 – 0.8	Vegetation boundary between land and water, and landforms.
Band 4 – Near Infrared	0.8 – 1.1	Penetrates atmospheric haze best, emphasizes vegetation, boundary between land and water, and landforms.

Table 2. Spectral band function for Landsat 5 TM/Landsat 7 ETM+ missions (*Source:* Headley, R. 2010. Landsat: A global land-imaging project. U.S. Geological Survey Fact Sheet 2010–3026.).

Spectral Band	Wavelength (nm)	Use for mapping:
Band 1 – Blue	0.45 – 0.52	Bathymetric features, distinguishing soil from vegetation and deciduous from coniferous vegetation.
Band 2 – Green	0.52 – 0.60	Emphasizes peak vegetation, which is useful for assessing plant vigor.
Band 3 – Red	0.63 – 0.69	Discriminates vegetation slopes.
Band 4 – Near Infrared	0.77 – 0.90	Emphasizes biomass content and shorelines.
Band 5 – Short-wave Infrared	1.55 – 1.75	Discriminates moisture content of soil and vegetation; penetrates thin clouds.
Band 6 – Thermal Infrared	10.40 – 12.50	Thermal mapping and estimating soil moisture.
Band 7 – Short-wave Infrared	2.09 – 2.35	Hydrothermally altered rocks associated with mineral deposits.
Band 8 – Panchromatic	0.52 – 0.90	15-meter resolution, sharper image definition. ETM+ (Landsat 7) only.

Table 3. General weather conditions observed during 2009 study season (*Source:* NWS. 2009. Records from the Bechler River (station index 48-0585-02), Mammoth Hot Springs (48-9905-01), Tower (48-9025-01) and Lake Yellowstone (48-5345-04) ranger stations as reported to the National Oceanic and Atmospheric Administration in July 2009.).

Date	Max. temp. (°C)	Min. temp. (°C)	Precip. (cm)	Weather station
9 July 2009	20.6	2.8	0.3	MHS
10 July 2009	21.7	4.4	0.1	MHS
11 July 2009	24.4	4.4	0	MHS
12 July 2009	27.8	2.8	0	TF
13 July 2009	29.4	2.8	0.5	TF
14 July 2009	21.7	4.4	0	TF
15 July 2009	15.0	2.8	0.1	LY
16 July 2009	20.0	3.3	0	LY
17 July 2009	23.3	3.9	0	LY
18 July 2009	23.3	4.4	0	LY
19 July 2009	26.1	6.7	0	LY
20 July 2009	22.8	4.4	0.3	LY
21 July 2009	21.7	3.3	0.2	LY
22 July 2009	23.8	5.0	0	LY
23 July 2009	30.6	10.0	0	MHS
24 July 2009	32.2	15.0	0	MHS
25 July 2009	18.3	6.1	0	LY
26 July 2009	22.8	6.7	0	LY
27 July 2009	27.8	6.7	0	BR

Note: Weather Station Identification:

MHS = Mammoth Hot Springs (elevation 1899 m)
TF = Tower Falls (elevation 1910 m)
LY = Lake Yellowstone (elevation 2399 m)
BR = Bechler River (elevation 1959 m)

Table 4. General weather conditions observed during 2010 study season (*Source:* NWS. 2010. Records from the Bechler River (station index: 48-0585-02), Mammoth Hot Springs (48-9905-01), Tower (48-9025-01) and Lake Yellowstone (48-5345-04) Ranger Stations as reported to the National Oceanic and Atmospheric Administration in August and September 2010.).

Date	**Max. temp. (°C)**	**Min. temp. (°C)**	**Precip. (cm)**	**Weather station**
16 Aug 2010	25.6	6.1	0	BR
17 Aug 2010	29.4	5.0	Trace	BR
18 Aug 2010	28.3	3.7	0	BR
19 Aug 2010	27.2	3.7	0	BR
20 Aug 2010	21.1	5.6	Trace	LY
21 Aug 2010	22.2	3.3	0	LY
22 Aug 2010	29.4	12.2	0	MHS
23 Aug 2010	21.1	0.6	0.1	LY
24 Aug 2010	13.9	-2.2	0.1	LY
25 Aug 2010	25.0	-0.6	0	TF
26 Aug 2010	30.6	0.6	0	TF
27 Aug 2010	31.1	11.1	0	MHS
28 Aug 2010	25.0	8.9	0	MHS
29 Aug 2010	15.6	6.1	1.7	MHS
30 Aug 2010	19.4	6.1	0.1	MHS
31 Aug 2010	13.3	2.8	0.1	MHS
1 Sept 2010	14.4	2.8	0.1	TF
2 Sept 2010	20.0	-2.8	Trace	TF
3 Sept 2010	18.9	2.8	0	MHS
4 Sept 2010	26.1	0.0	0	TF
5 Sept 2010	26.7	8.9	0	MHS
6 Sept 2010	15.6	-5.0	0.3	LY
7 Sept 2010	1.7	-4.4	0	TF
8 Sept 2010	16.1	-2.8	0	LY

Table 5. Species occurrence of vascular plants sampled at nesting territories.

Family	Scientific name	Percent Occurrence of Species
Ceratophyllaceae	*Ceratophyllum demursum*	27%
Cupressaceae	*Juniperus communis*	6%
Cyperaceae	*Carex aquatilis*	30%
	Carex utriculata	33%
	Eleocharis palustris	21%
	Schoenoplectus acutus	36%
Ericaceae	*Vaccinium occidentale*	3%
Hippuridaceae	*Hippuris vulgaris*	9%
Hydrocharitaceae	*Elodea canadensis*	6%
Juncaceae	*Juncus articulatus*	3%
Lemnaceae	*Lemna turionifera*	21%
Marsileaceae	*Marsilea vestita*	3%
Najadaceae	*Najas guadalupensis*	6%
Nymphaeaceae	*Nuphar polysepala*	36%
Poaceae	*Agrostis scabra*	3%
	Hordeum brachyantherum	3%
	Phalaris arundinacea	3%
Polygonaceae	*Polygonum amphibium*	9%
	Rumex crispus	3%
Portulacaceae	*Claytonia lanceolata*	3%
Potamogetonaceae	*Stuckenia filiformis*	33%
	Stuckenia pectinata	18%
	Potamogeton crispus	9%
	Potamogeton epihydrus	9%
	Potamogeton gramineus	6%
	Potamogeton natans	27%
	Potamogeton nodosus	3%
	Potamogeton pusillus	6%
	Potamogeton robbinsii	6%
Ranunculaceae	*Ranunculus aquatilis*	6%
Rosaceae	*Pentaphylloides floribunda*	3%
	Potentilla palustris	3%
Salicaceae	*Salix glauca*	9%
	Populus tremuloides	3%
Scrophulariaceae	*Limosella aquatica*	3%
Typhaceae	*Typha latifolia*	21%

Table 6. Geographic characteristics of historical nesting locations in YNP (including total size of continuous wetland habitat within 5.0 km of historic nesting location, dominant habitat type within foraging territory, elevation of nesting territory, and island availability within nesting territories as determined from NWI maps).

Territory Name	**Size (ha)**	**Dominate habitat (%)**	**Elevation (m)**	**Islands Available**
Alum Creek	116	86% Palustrine	2352	Yes
Beach Springs Lagoon	25	58% Lacustrine Littoral	2371	No
Bechler Meadows	2068	80% Palustrine	1960	Yes
Beula Lake	141	42% Palustrine	2265	No
Blacktail Ponds	36	90% Palustrine	2025	Yes
Cascade Lake	42	67% Palustrine	2445	Yes
Crescent Lake	5	73% Lacustrine Limnetic	2622	No
Cygnet Lakes	131	81% Palustrine	2537	Yes
East Tern Lake	165	73% Palustrine	2512	Yes
Geode Lake	4	74% Lacustrine Littoral	1833	No
Grebe Lake	112	38% Lacustrine Limnetic	2475	Yes
Grizzly Lake	120	49% Palustrine	2300	No
Harlequin Lake	8	51% Lacustrine Limnetic	2105	No
Hellroaring Complex	4	100% Palustrine	2314	No
Hidden Lakes	78	50% Lacustrine Littoral	2402	Yes
Lake of the Woods	21	47% Palustrine	2375	No
LeHardy Rapids	383	56% Palustrine	2363	Yes
Lilypad Lake	220	58% Palustrine	1961	Yes
McBride Lake	15	71% Lacustrine Limnetic	2014	No
Mt. Everts Lake	10	100% Palustrine	2224	No

Table 6 (continued).

Territory Name	Size (ha)	Dominate habitat (%)	Elevation (m)	Islands Available
Obsidian Lake	11	78% Lacustrine Littoral	2366	No
Pelican Creek	331	76% Palustrine	2370	Yes
Phoneline Lake	112	94% Palustrine	1945	Yes
Rainbow Lakes	4	57% Palustrine	1807	No
Riddle Lake	540	68% Palustrine	2423	Yes
Robinson Lake	127	86% Palustrine	1996	Yes
Seven Mile Bridge	129	50% Riverine	2066	No
Slough Creek Ponds	2	100% Palustrine	1926	No
South Twin Lake	278	76% Palustrine	2309	Yes
Sportsman Lake	15	87% Palustrine	2361	No
Swan Lake	97	82% Palustrine	2222	Yes
Trout Lake	5	67% Lacustrine Limnetic	2138	No
Trumpeter Lakes	21	49% Lacustrine Limnetic	1874	No
White Lake	84	62% Lacustrine Limnetic	2523	Yes
Winegar Lake	17	44% Lacustrine Littoral	1967	No
Wolf Lake	101	82% Palustrine	2452	Yes

Table 7. Calculated raw NDVI values for historical nesting locations in YNP.

Territory Name	2005 ETM+	1999 TM	1990 TM	1979 MSS	1975 MSS
Alum Creek	0.52	0.24	0.24	0.34	0.47
Beach Springs Lagoon	0.26	0.09	0.04	0.14	0.21
Bechler Meadows	0.55	0.28	0.26	0.36	0.44
Beula Lake	0.14	0.03	-0.06	-0.03	0.07
Blacktail Ponds	0.38	0.16	0.15	0.24	0.26
Cascade Lake	0.45	0.17	0.17	0.28	0.39
Crescent Lake	-0.05	-0.25	-0.30	-0.11	0.10
Cygnet Lakes	0.48	0.26	0.22	0.31	0.41
East Tern Lake	0.53	0.27	0.30	0.37	0.43
Geode Lake	-0.02	-0.01	-0.14	-0.01	-0.00
Grebe Lake	0.24	0.06	0.02	0.05	0.17
Grizzly Lake	0.24	0.05	-0.01	0.08	0.18
Harlequin Lake	0.35	0.14	0.10	0.31	0.33
Hellroaring Complex	0.26	0.08	0.10	0.14	0.13
Hidden Lakes	0.45	0.22	0.22	0.37	0.41
Lake of the Woods	0.37	0.15	0.16	0.29	0.29
LeHardy Rapids	0.32	0.13	0.12	0.22	0.27
Lilypad Lake	0.49	0.25	0.24	0.32	0.38
McBride Lake	0.19	0.03	-0.05	0.10	0.19
Mt. Everts Lake	0.23	-0.01	-0.10	0.12	0.26
Obsidian Lake	0.38	0.15	0.14	0.32	0.32
Pelican Creek	0.55	0.27	0.28	0.36	0.46

Table 7 (continued).

Territory Name	**2005 ETM+**	**1999 TM**	**1990 TM**	**1979 MSS**	**1975 MSS**
Phoneline Lake	0.59	0.30	0.26	0.38	0.48
Rainbow Lakes	0.12	-0.05	-0.04	0.08	0.12
Riddle Lake	0.41	0.18	0.20	0.28	0.36
Robinson Lake	0.56	0.31	0.30	0.41	0.46
Seven Mile Bridge	0.38	0.20	0.17	0.29	0.26
Slough Creek Ponds	0.12	-0.07	0.07	0.20	0.10
South Twin Lake	0.35	0.16	0.18	0.27	0.28
Sportsman Lake	0.57	0.28	0.29	0.38	0.42
Swan Lake	0.41	0.16	0.18	0.25	0.34
Trout Lake	0.05	-0.05	-0.22	-0.17	0.22
Trumpeter Lakes	0.16	-0.03	-0.04	0.02	0.11
White Lake	0.02	-0.09	-0.20	0.13	0.11
Winegar Lake	0.36	0.14	0.10	0.23	0.26
Wolf Lake	0.50	0.21	0.23	0.30	0.40

Table 8. Calculated positive NDVI values for historical nesting locations in YNP.

Territory Name	2005 ETM+	1999 TM	1990 TM	1979 MSS	1975 MSS
Alum Creek	0.52	0.25	0.25	0.34	0.47
Beach Springs Lagoon	0.56	0.35	0.37	0.35	0.43
Bechler Meadows	0.55	0.28	0.26	0.36	0.44
Beula Lake	0.43	0.29	0.28	0.33	0.32
Blacktail Ponds	0.40	0.19	0.18	0.24	0.26
Cascade Lake	0.58	0.27	0.34	0.42	0.51
Crescent Lake	0.23	0.23	0.24	0.27	0.26
Cygnet Lakes	0.49	0.28	0.25	0.31	0.41
East Tern Lake	0.55	0.30	0.33	0.39	0.44
Geode Lake	0.14	0.10	0.14	0.21	0.11
Grebe Lake	0.48	0.26	0.32	0.39	0.41
Grizzly Lake	0.53	0.25	0.32	0.36	0.41
Harlequin Lake	0.41	0.19	0.20	0.31	0.34
Hellroaring Complex	0.26	0.13	0.12	0.14	0.13
Hidden Lakes	0.46	0.23	0.25	0.37	0.42
Lake of the Woods	0.43	0.21	0.28	0.36	0.35
LeHardy Rapids	0.51	0.30	0.30	0.32	0.39
Lilypad Lake	0.50	0.27	0.27	0.34	0.40
McBride Lake	0.39	0.24	0.28	0.26	0.27
Mt. Everts Lake	0.39	0.20	0.12	0.26	0.37
Obsidian Lake	0.39	0.17	0.18	0.32	0.33
Pelican Creek	0.57	0.29	0.29	0.36	0.47

Table 8 (continued).

Territory Name	**2005 ETM+**	**1999 TM**	**1990 TM**	**1979 MSS**	**1975 MSS**
Phoneline Lake	0.59	0.30	0.26	0.38	0.48
Rainbow Lakes	0.17	0.09	0.12	0.13	0.12
Riddle Lake	0.48	0.23	0.28	0.36	0.42
Robinson Lake	0.56	0.31	0.30	0.41	0.46
Seven Mile Bridge	0.41	0.27	0.27	0.29	0.27
Slough Creek Ponds	0.12	0.09	0.11	0.20	0.10
South Twin Lake	0.38	0.22	0.26	0.29	0.31
Sportsman Lake	0.61	0.33	0.36	0.41	0.45
Swan Lake	0.53	0.23	0.26	0.30	0.40
Trout Lake	0.42	0.23	0.22	0.26	0.32
Trumpeter Lakes	0.22	0.17	0.17	0.19	0.19
White Lake	0.30	0.20	0.22	0.29	0.28
Winegar Lake	0.46	0.26	0.28	0.33	0.35
Wolf Lake	0.53	0.26	0.31	0.37	0.44

APPENDIX C:

LANDSAT IMAGES

Viewer-subjective evaluations utilized Landsat composite images with a false-coloration applied. The MSS images (1975 and 1979) were created using an R-G-B composite of 4-2-1 while the TM and ETM+ images (1990, 1999, and 2005) were created using an R-G-B composite of 4-3-2. Each image is displayed in a 1:60,000 scale unless otherwise noted, with the YNP image displayed at a 1:1,500,000 scale for location purposes. Sites sampled in 2009 are marked with green dots, while sites sampled in 2010 are marked with blue dots. The images are displayed, in order:

a) 1975 MSS;
b) 1979 MSS;
c) 1990 TM;
d) 1999 ETM+;
e) 2005 ETM+;
f) YNP location map.

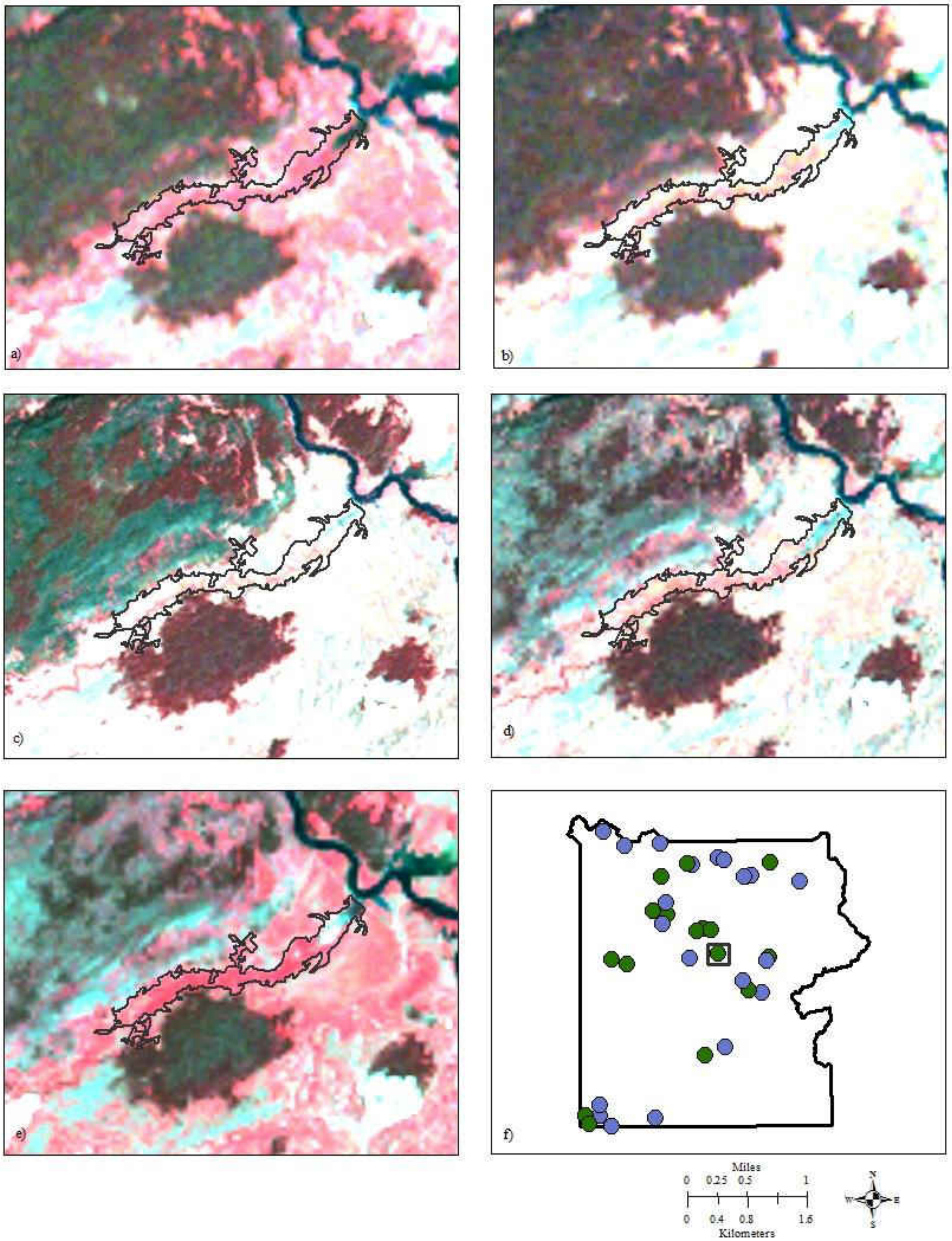

Figure 21. Landsat image of the Alum Creek historical nesting site.

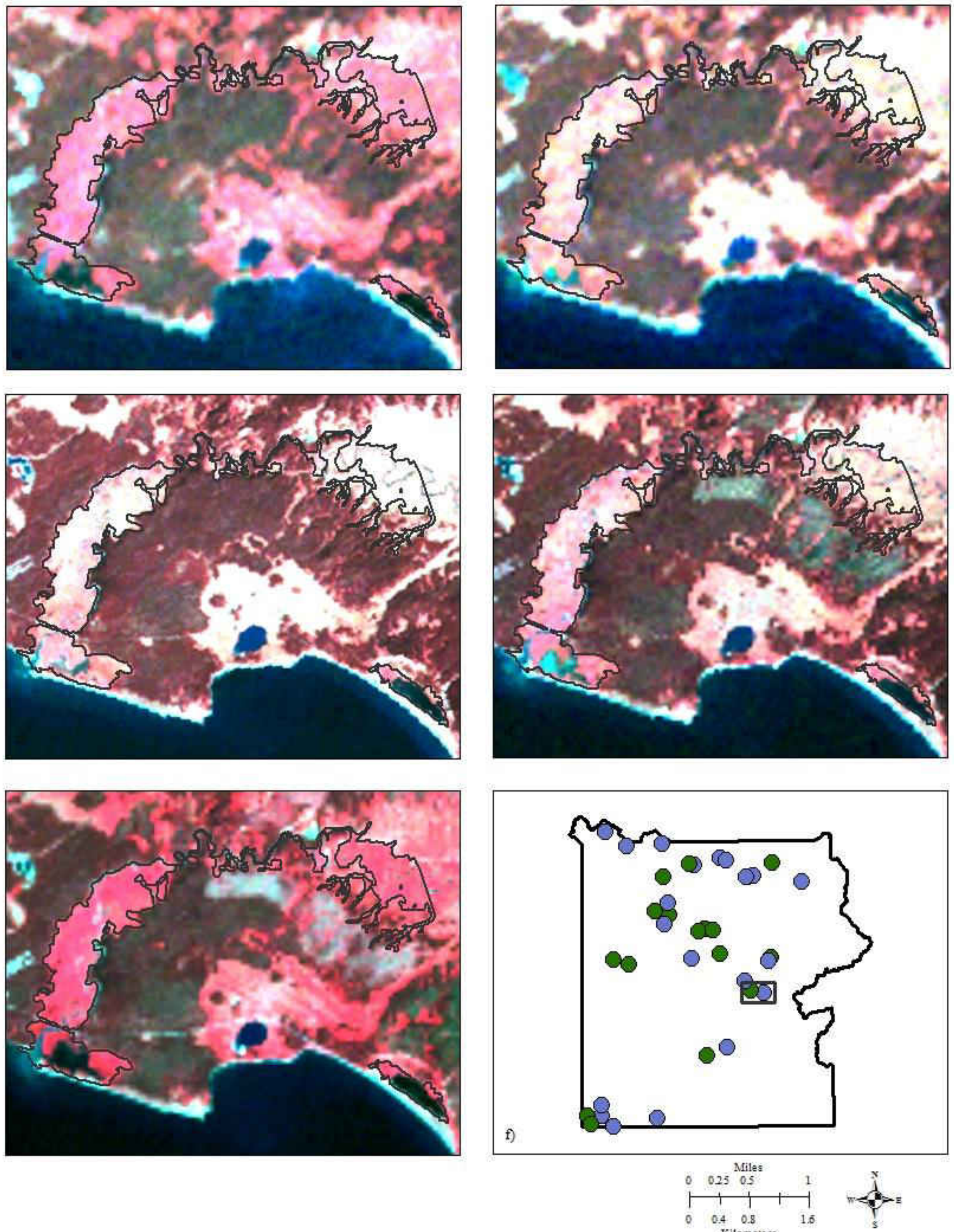

Figure 22. Landsat image of the Beach Springs Lagoon and Pelican Creek historical nesting sites.

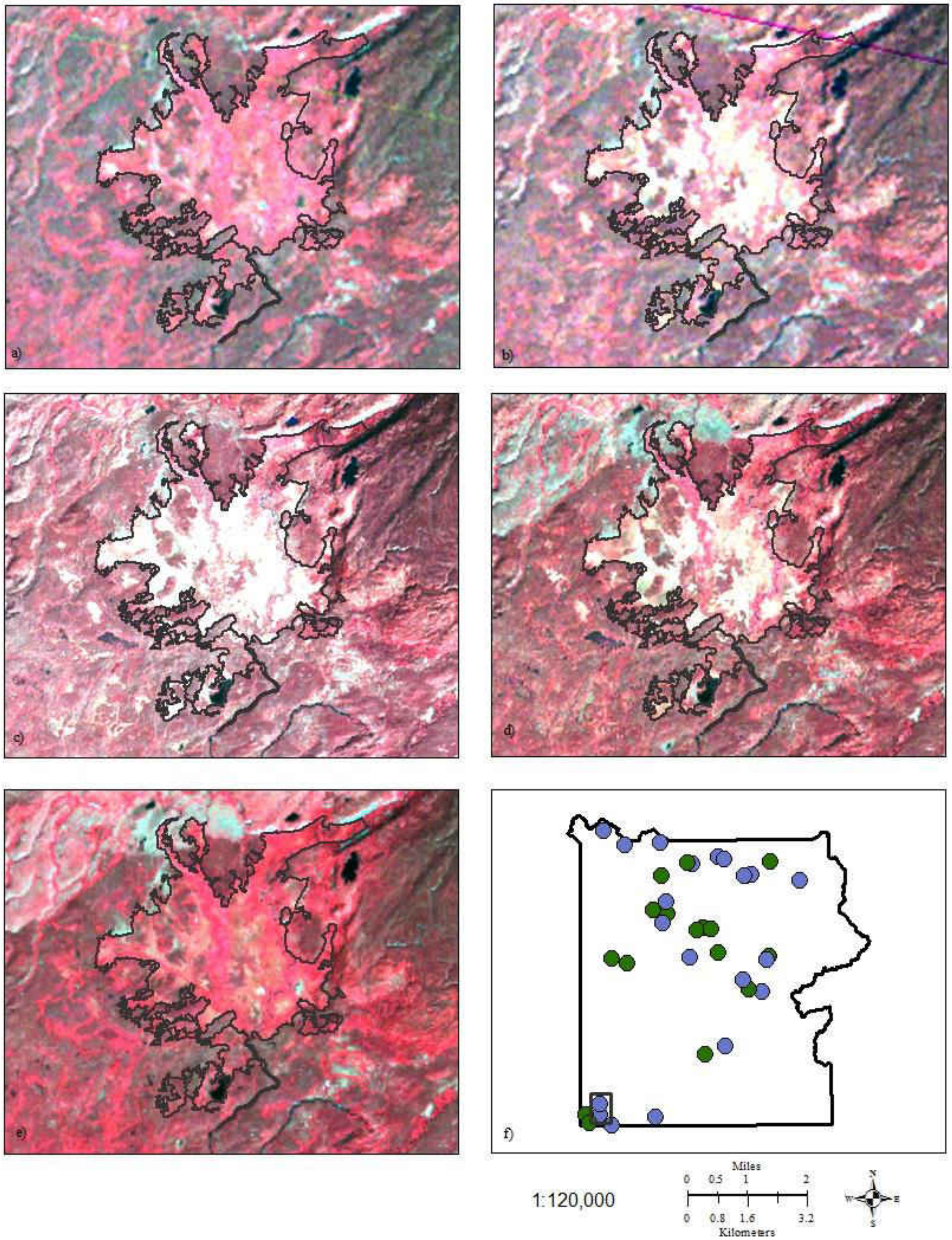

Figure 23. Landsat image of the Bechler Meadows and Lilypad Lake historical nesting sites.

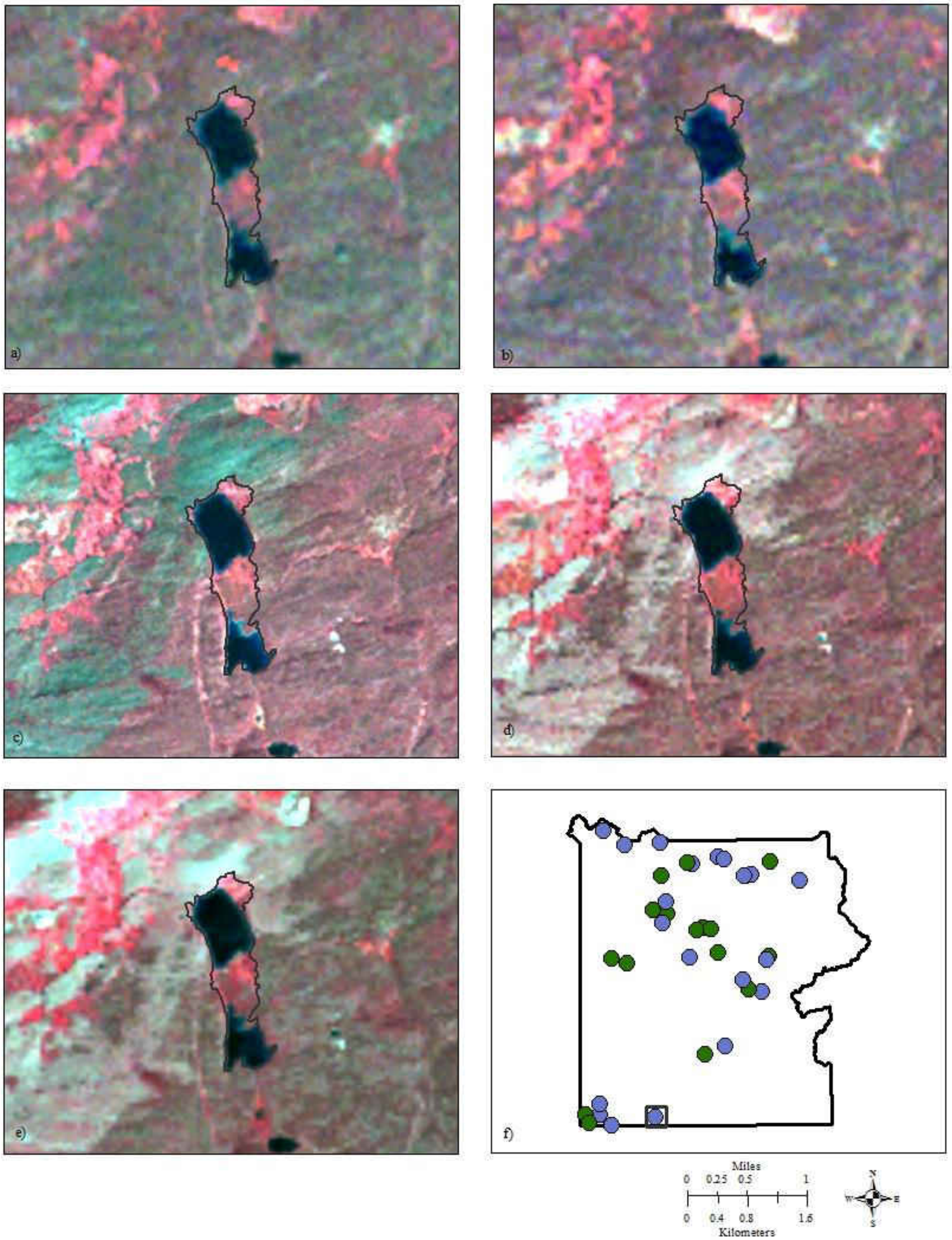

Figure 24. Landsat image of the Beula Lake historical nesting site.

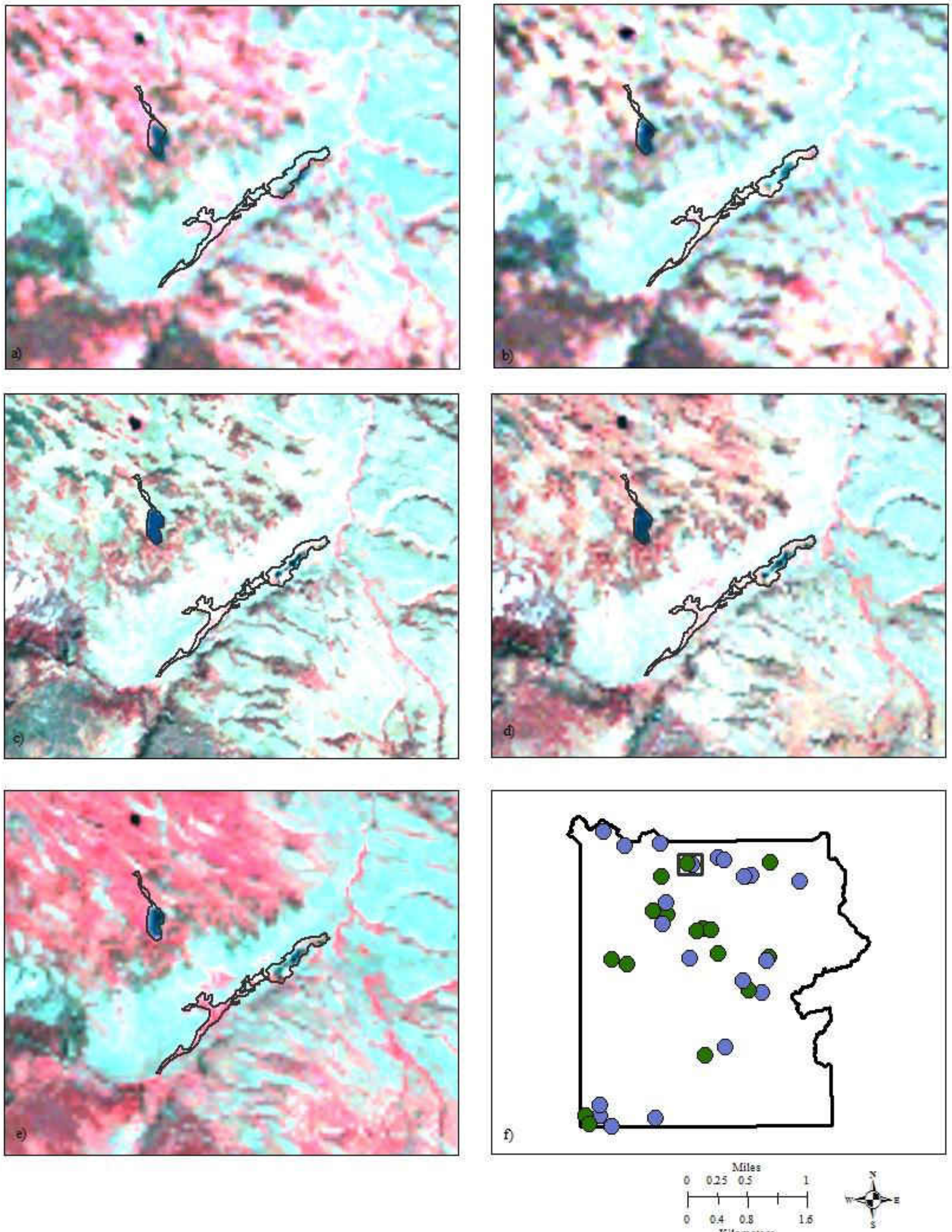

Figure 25. Landsat image of the Blacktail Ponds and Mount Everts Lake historical nesting sites.

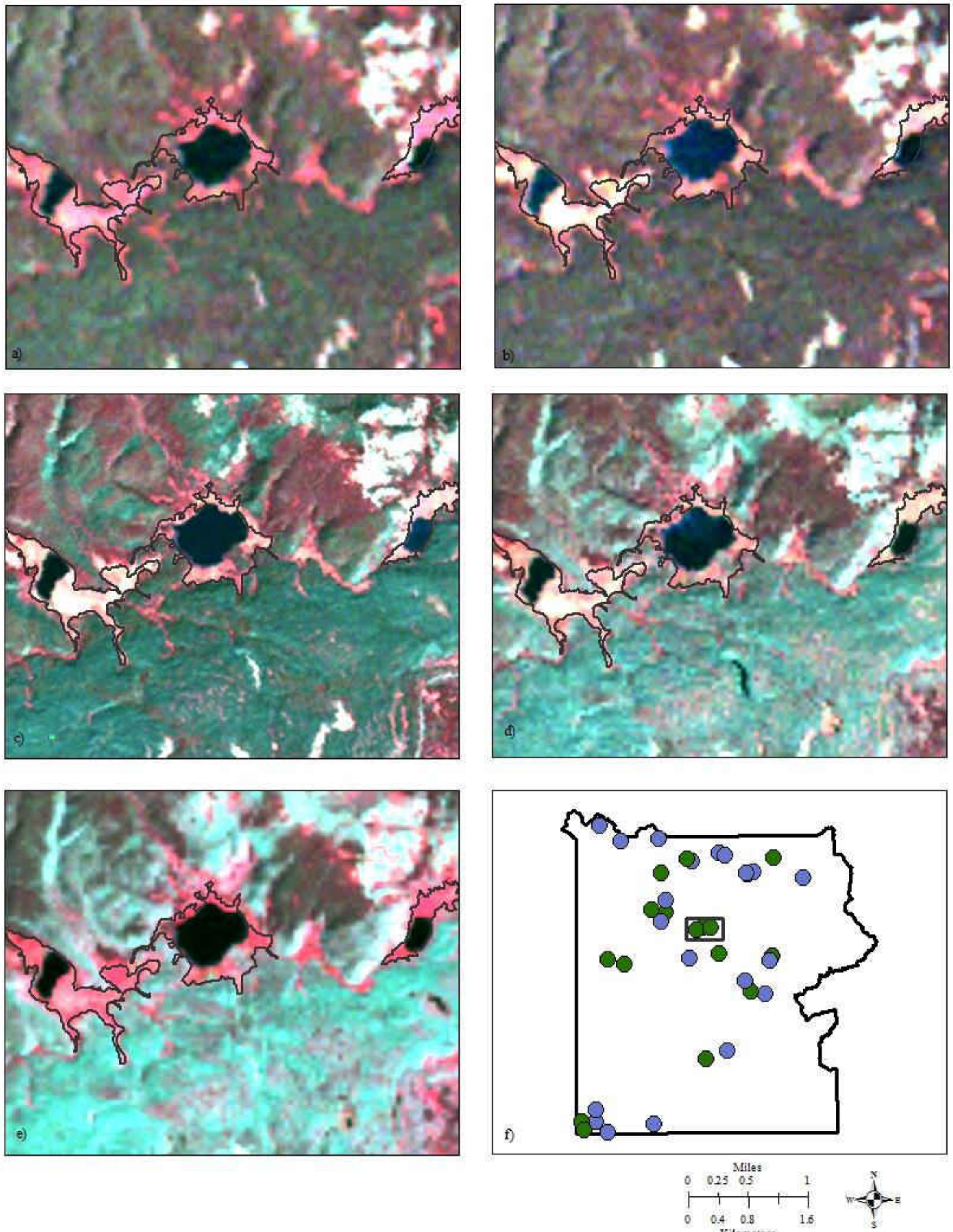

Figure 26. Landsat image of the Cascade Lake, Grebe Lake, and Wolf Lake historical nesting sites.

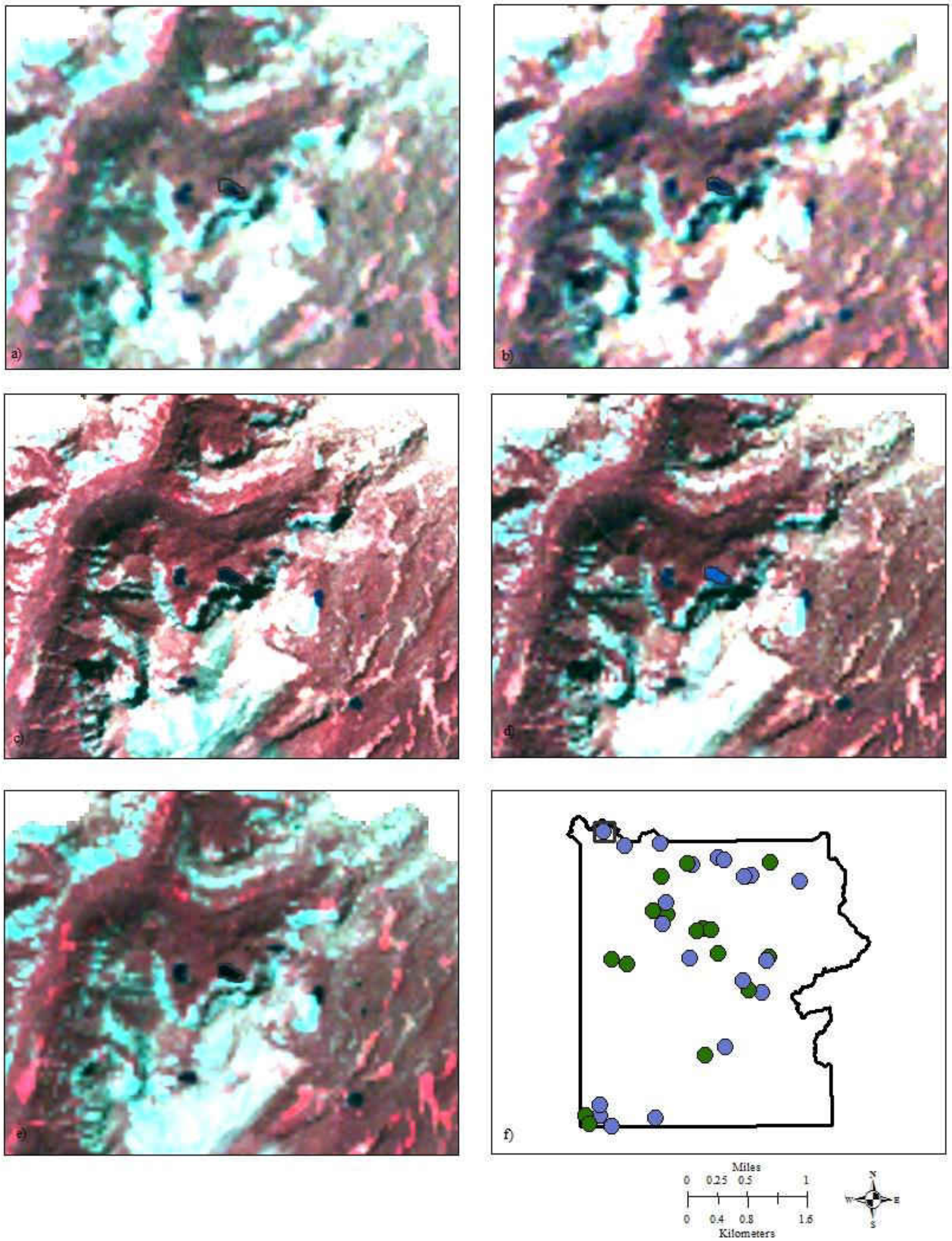

Figure 27. Landsat image of the Crescent Lake historical nesting site.

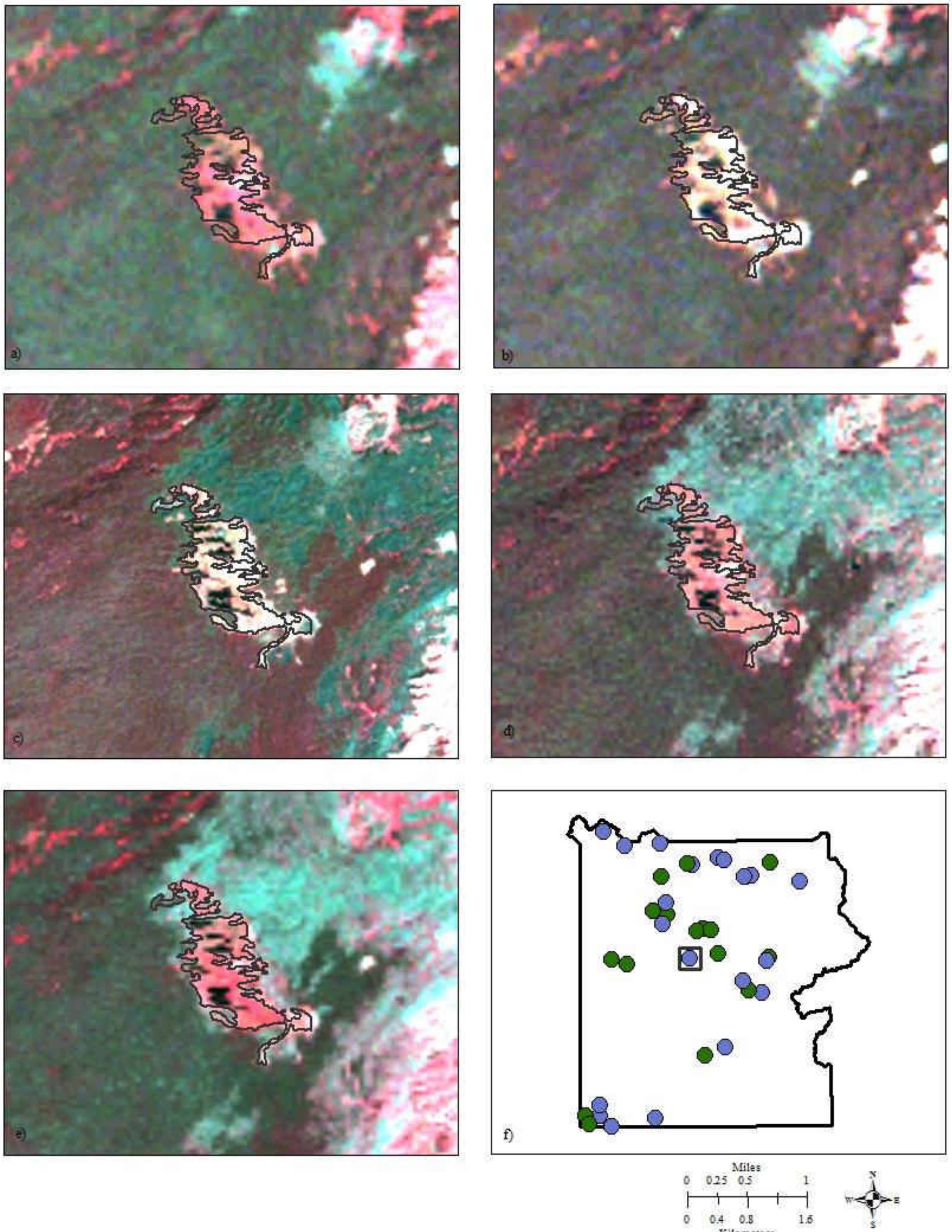

Figure 28. Landsat image of the Cygnet Lakes historical nesting site.

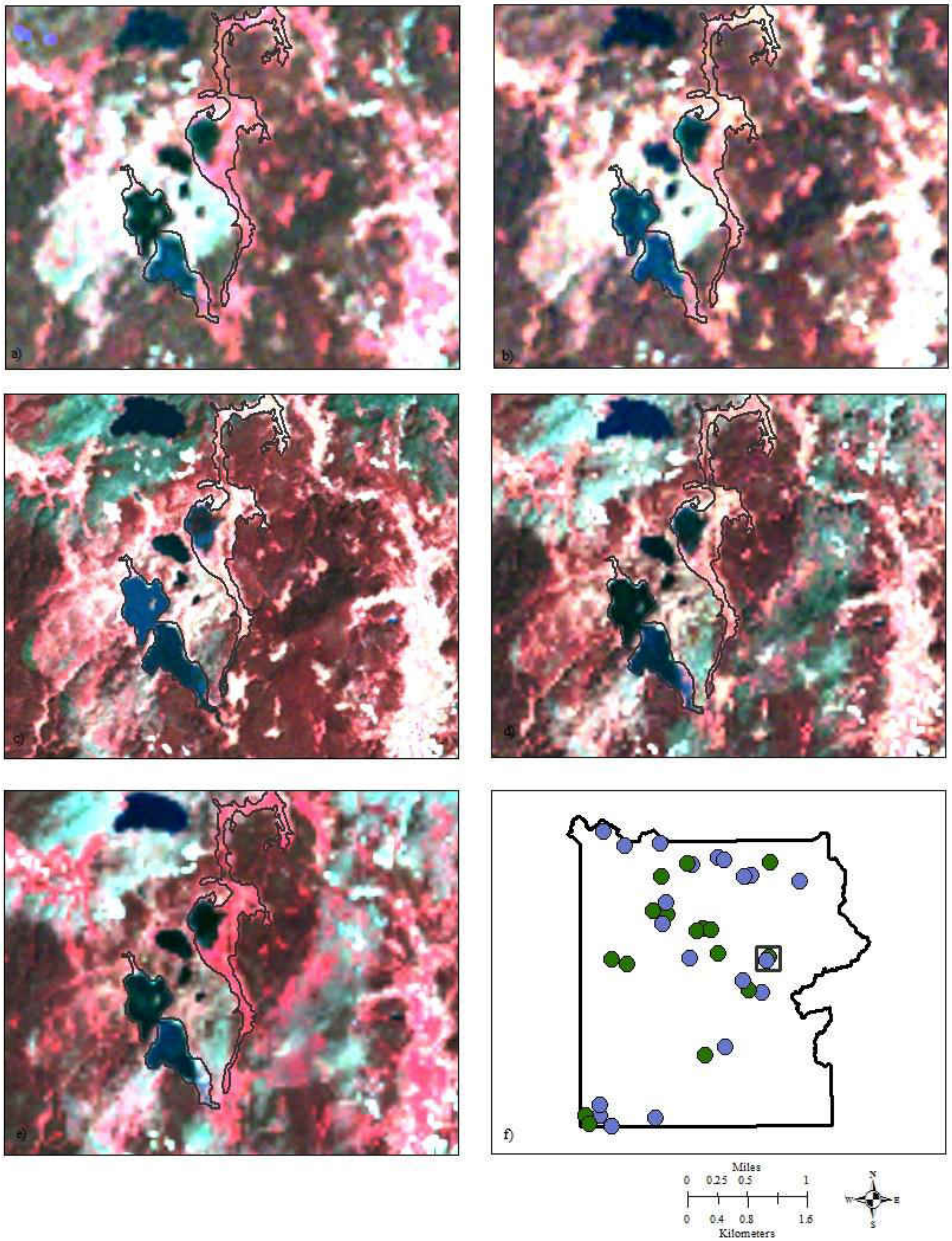

Figure 29. Landsat image of the East Tern Lake and White Lake historical nesting sites.

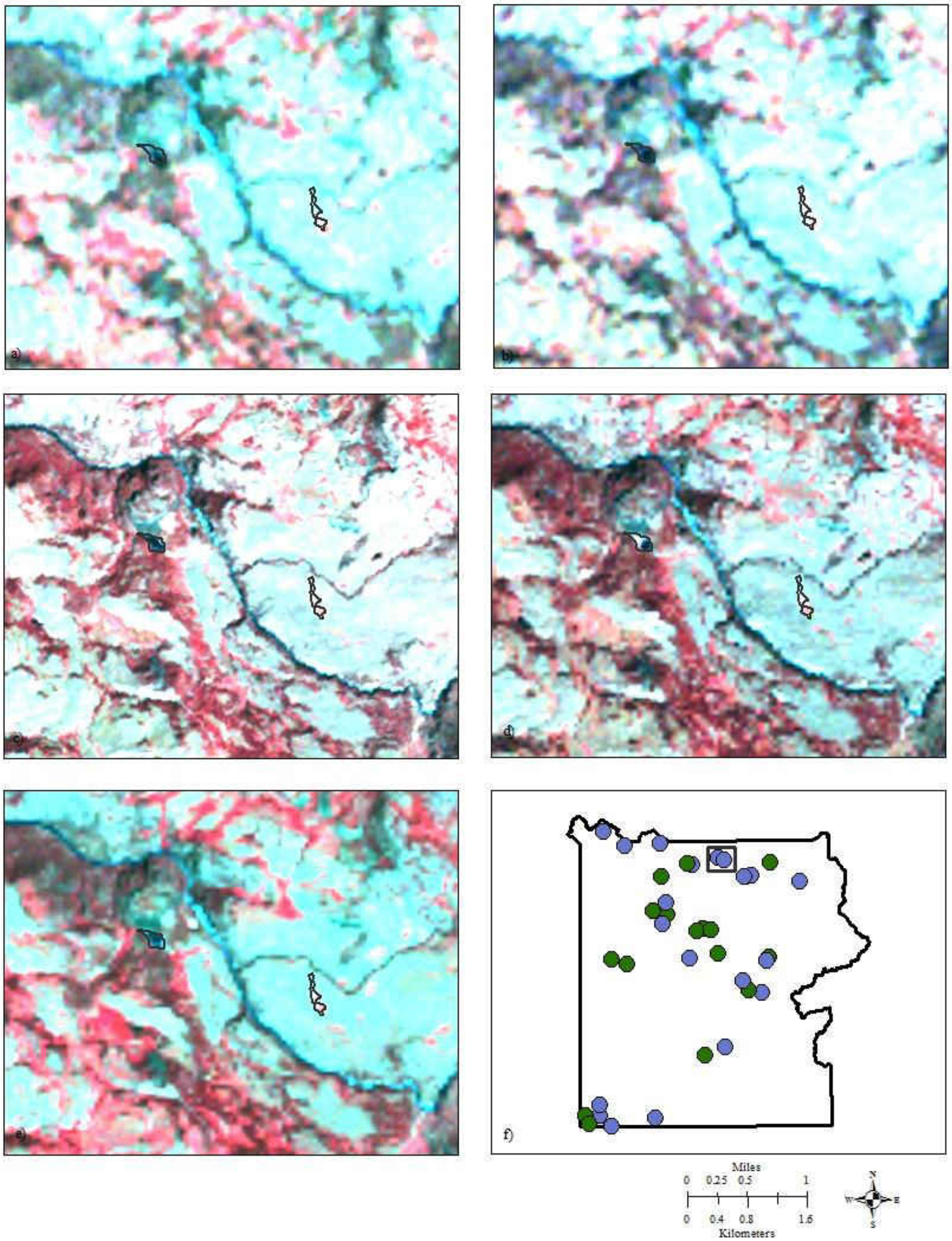

Figure 30. Landsat image of the Geode Lake and the Hellroaring Complex historical nesting sites.

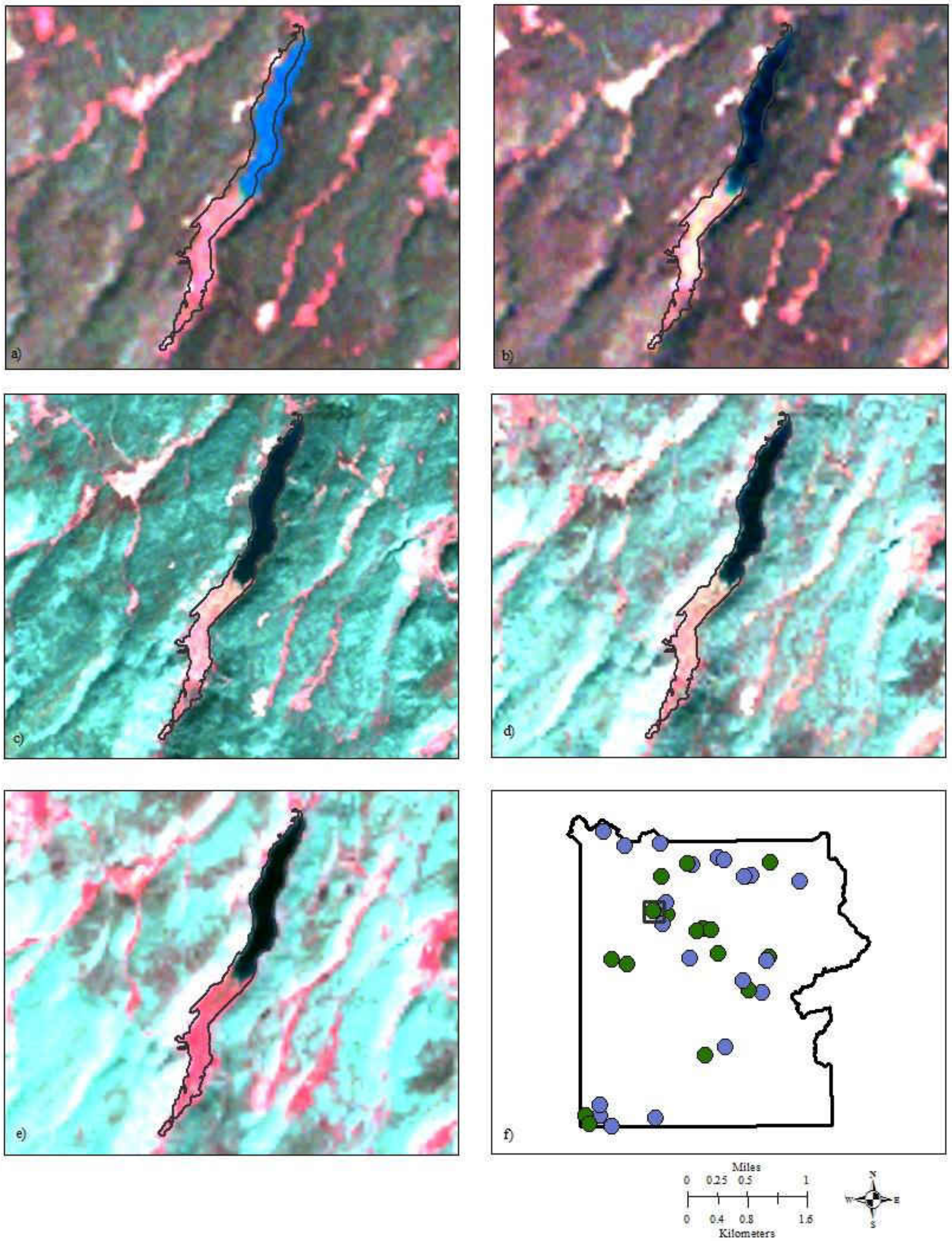

Figure 31. Landsat image of the Grizzly Lake historical nesting site.

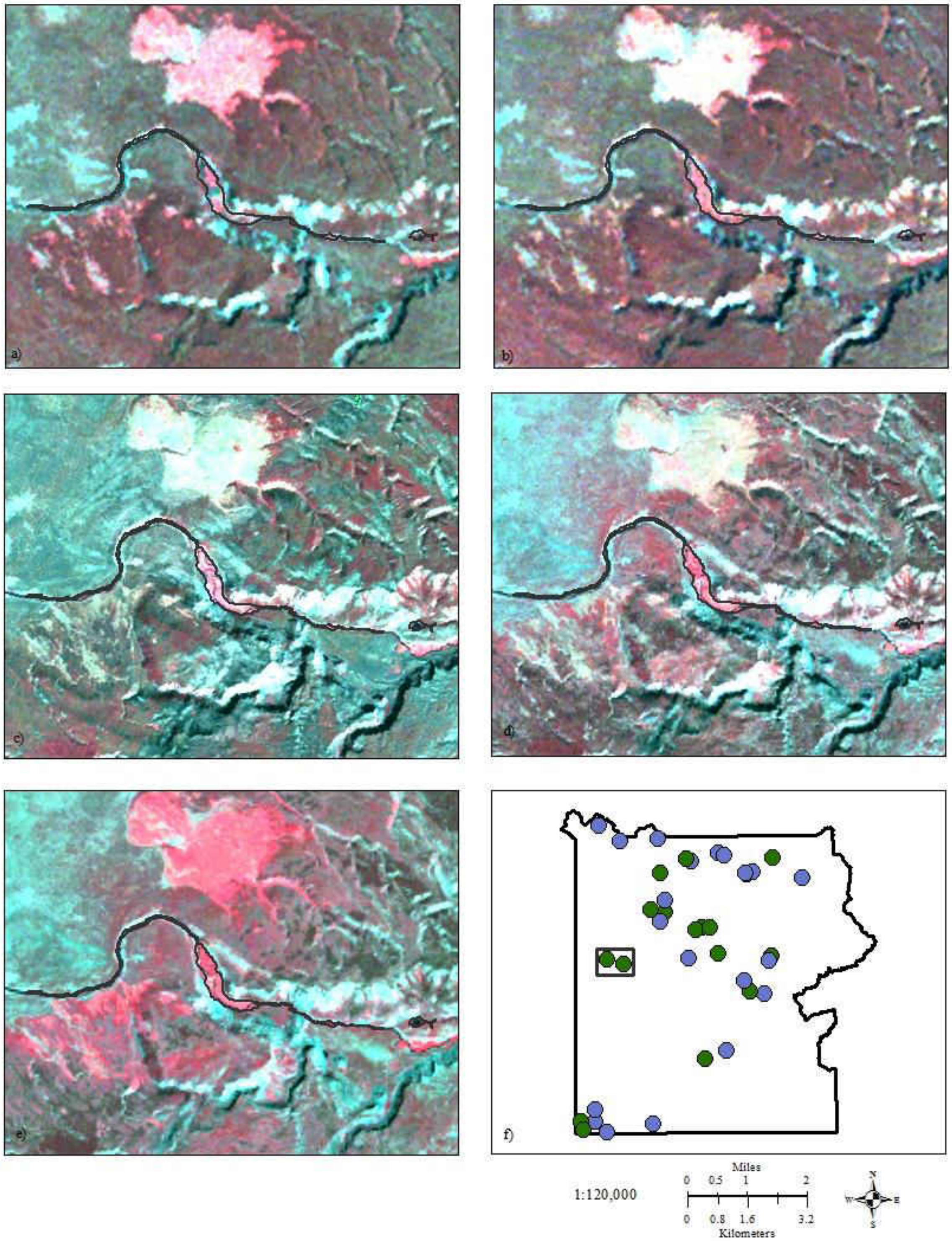

Figure 32. Landsat image of the Harlequin Lake and Seven Mile Bridge historical nesting sites.

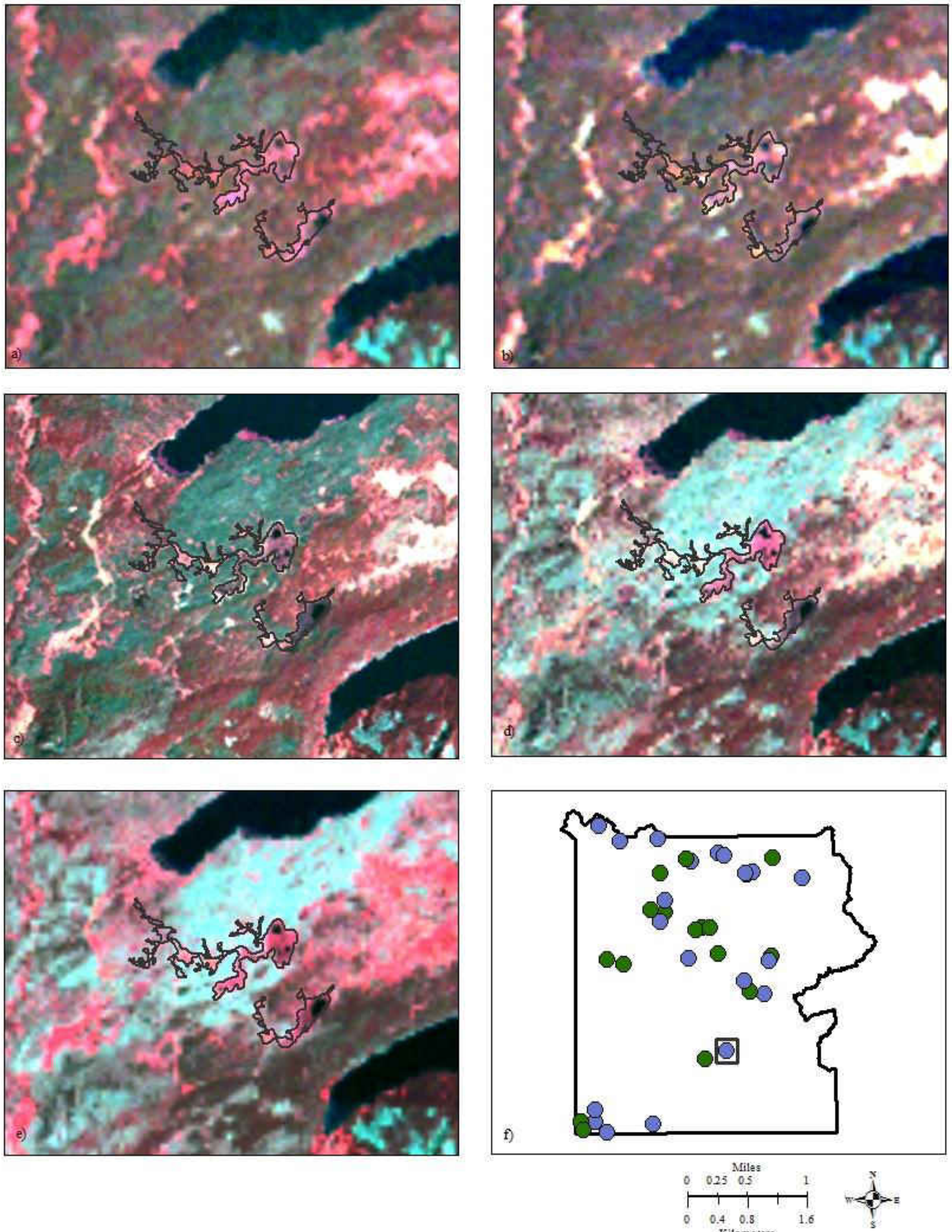

Figure 33. Landsat image of the Hidden Lakes historical nesting site.

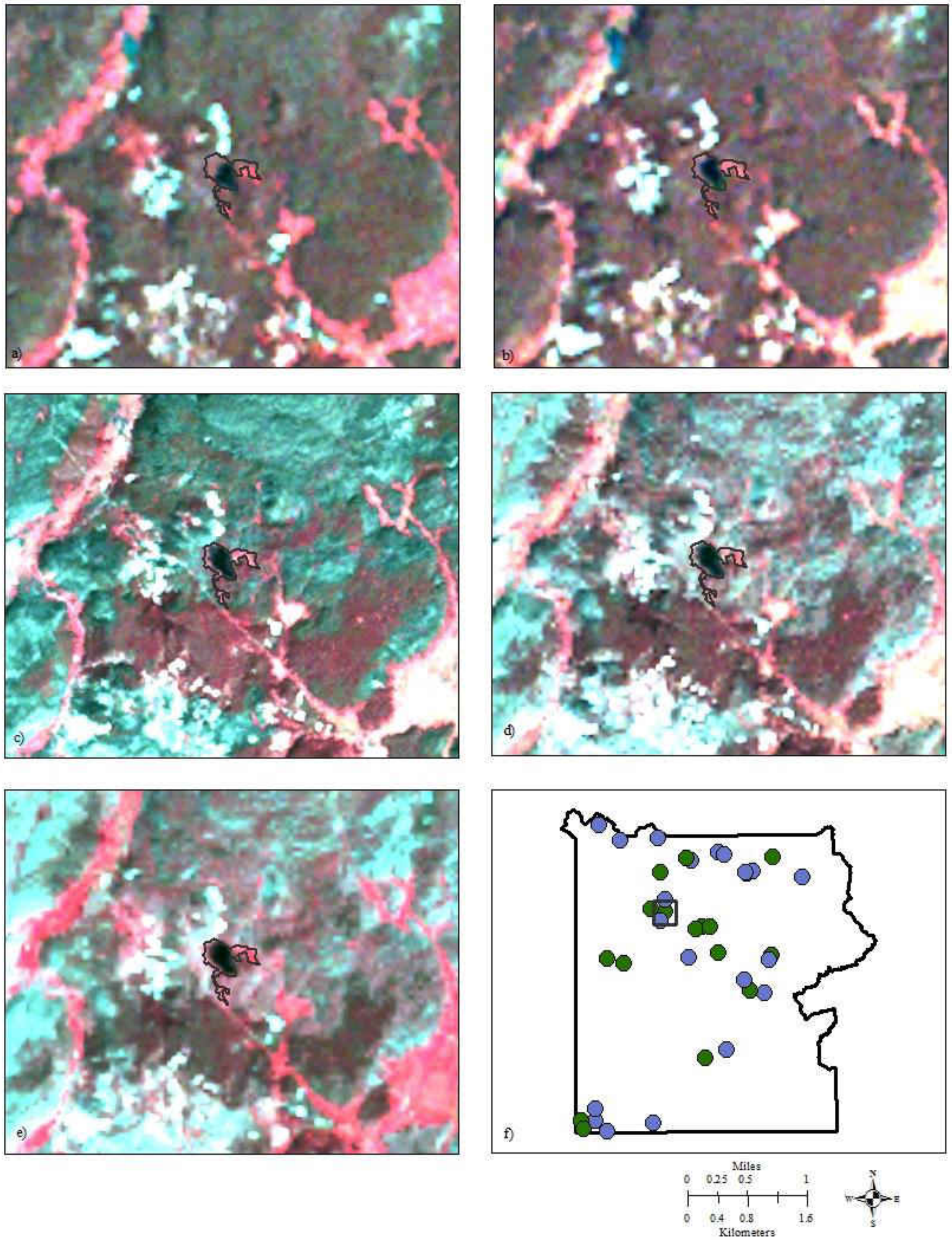

Figure 34. Landsat image of the Lake of the Woods historical nesting site.

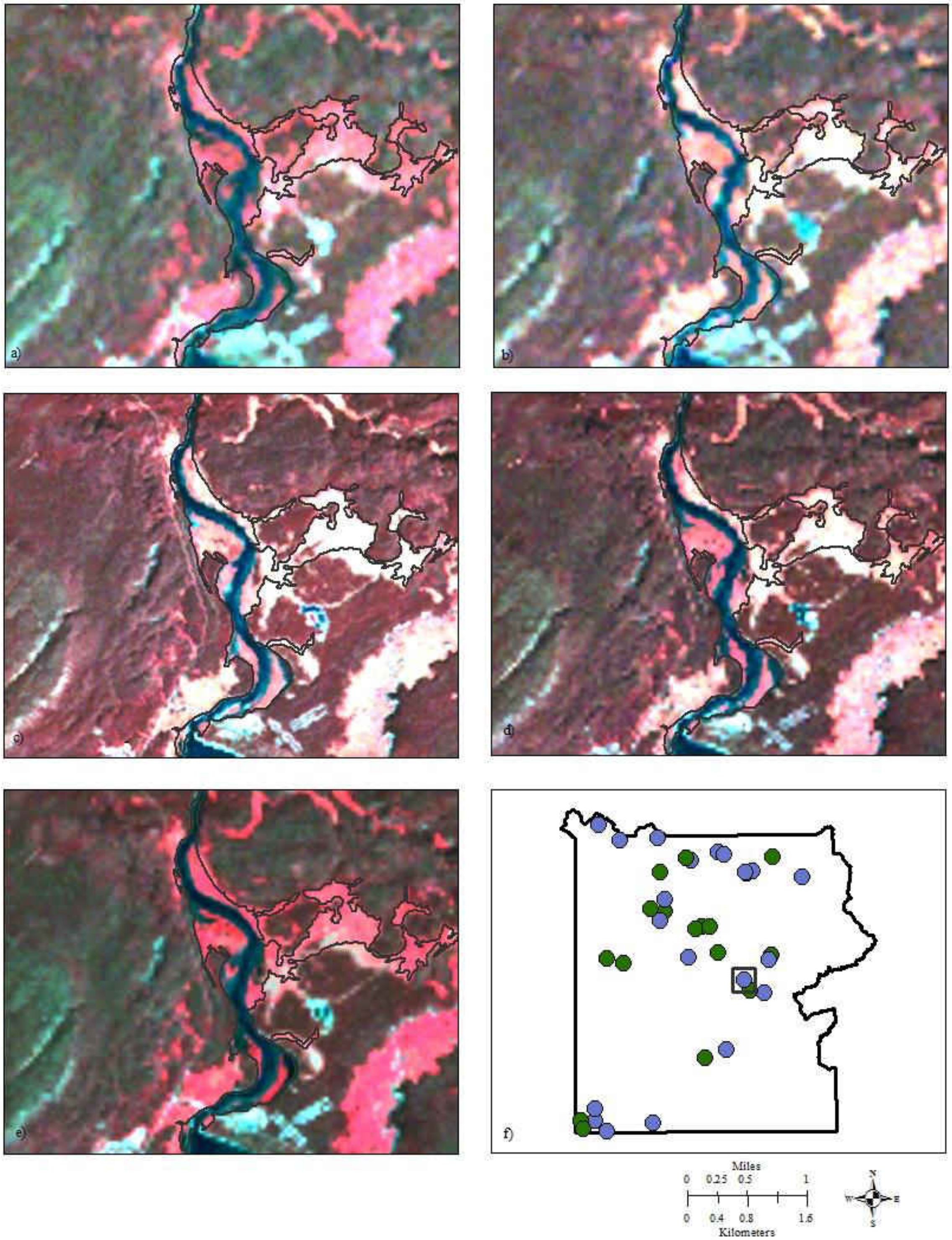

Figure 35. Landsat image of the LeHardy Rapids to Fishing Bridge historical nesting site.

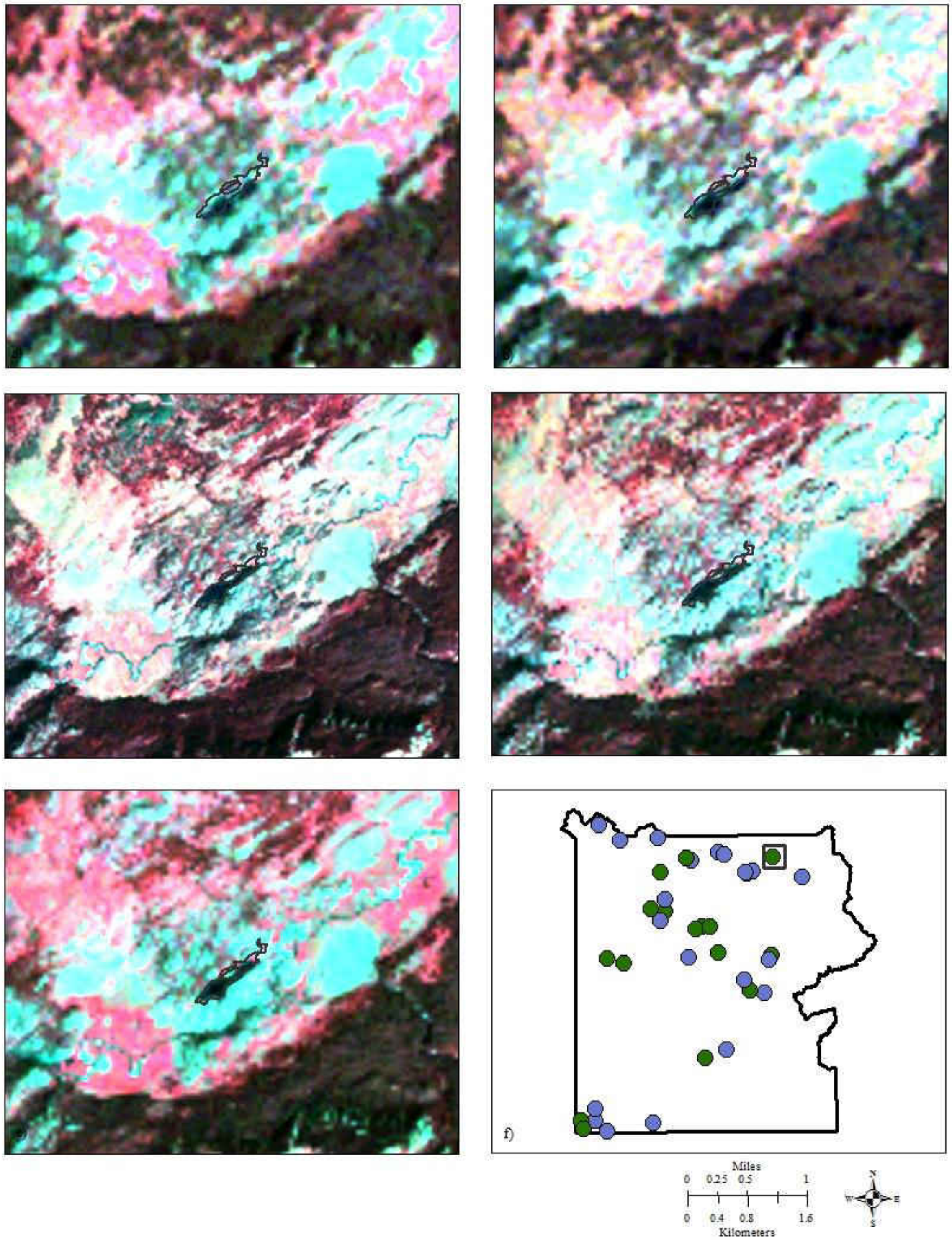

Figure 36. Landsat image of the McBride Lake historical nesting site.

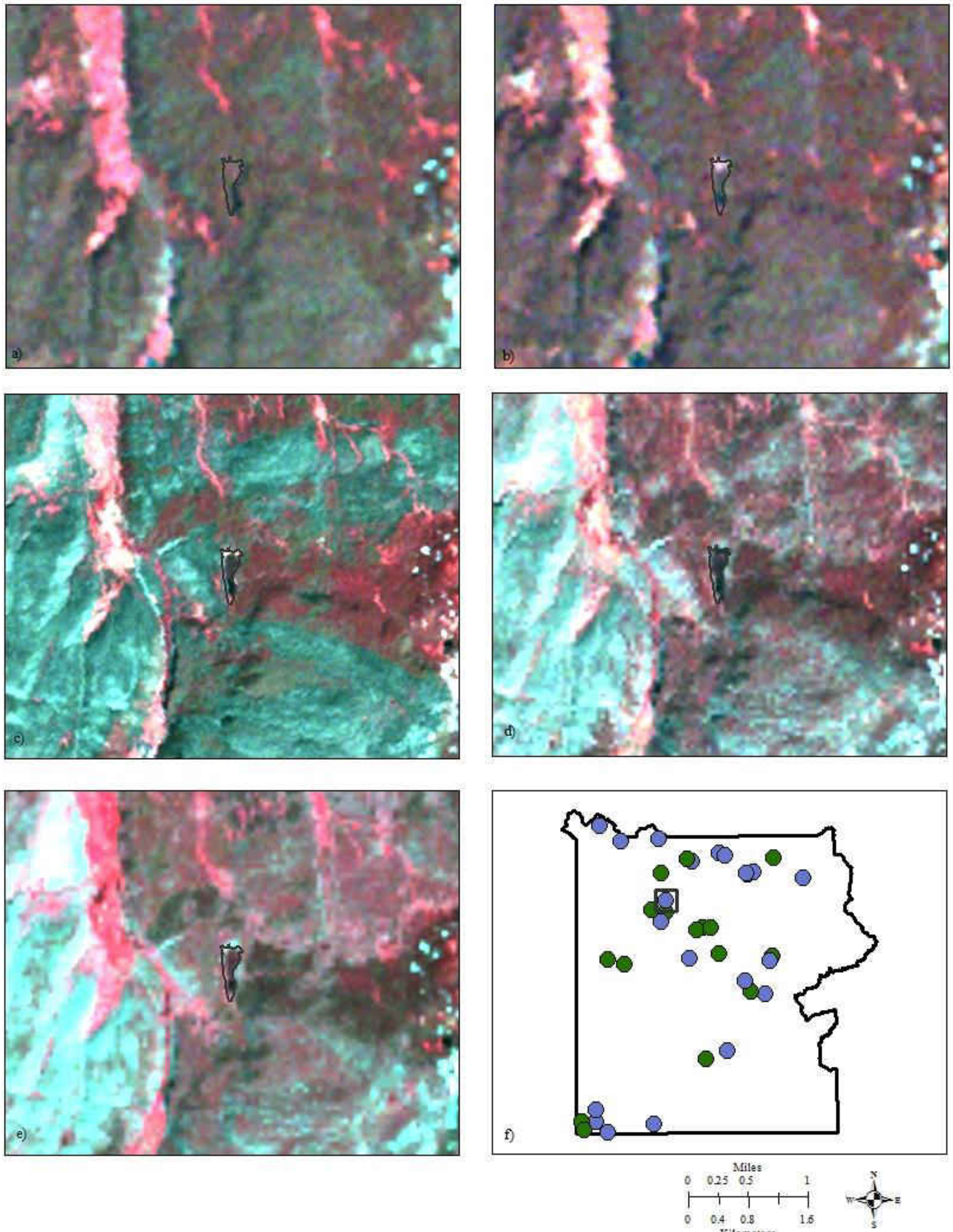

Figure 37. Landsat image of the Obsidian Lake historical nesting site.

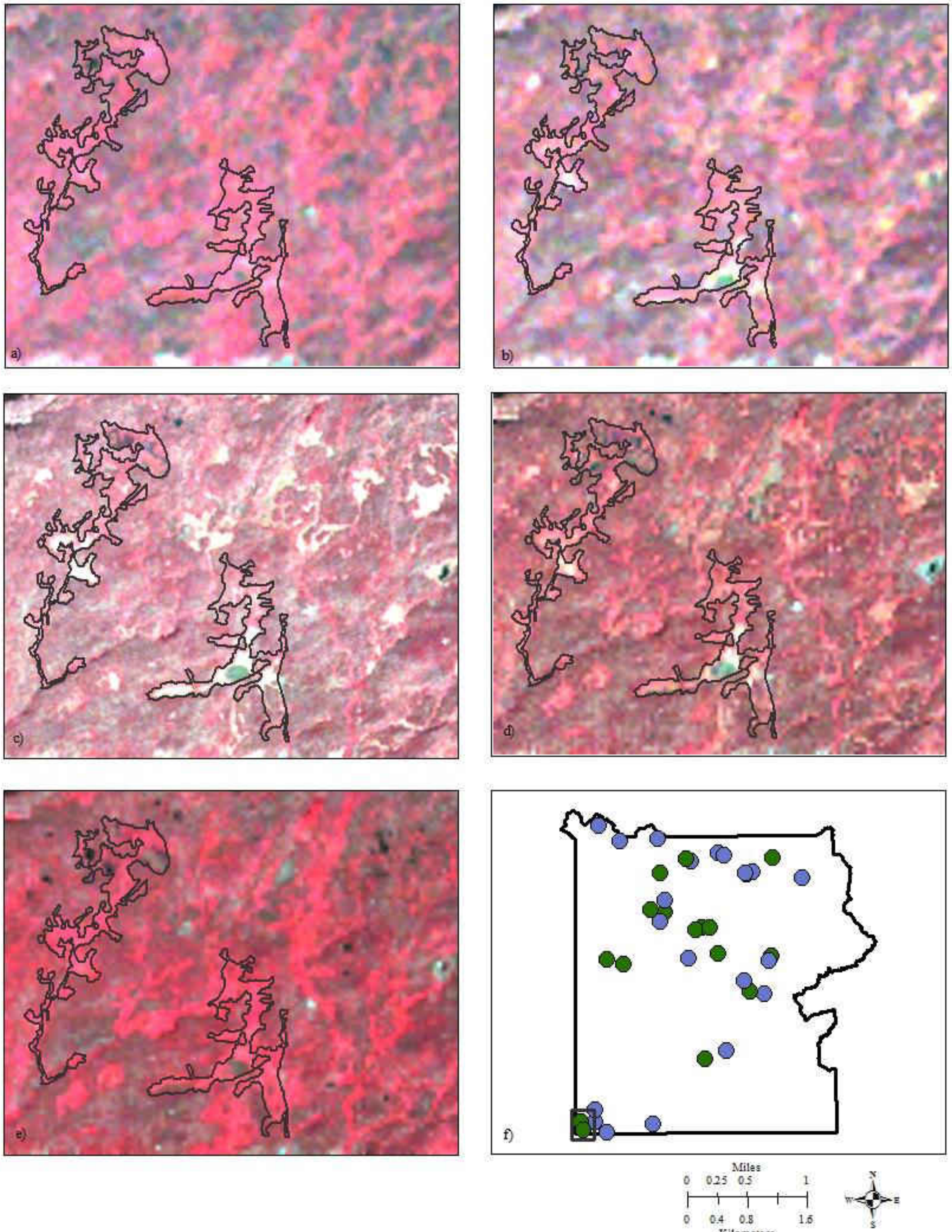

Figure 38. Landsat image of the Phoneline Lake and Robinson Lake historical nesting sites.

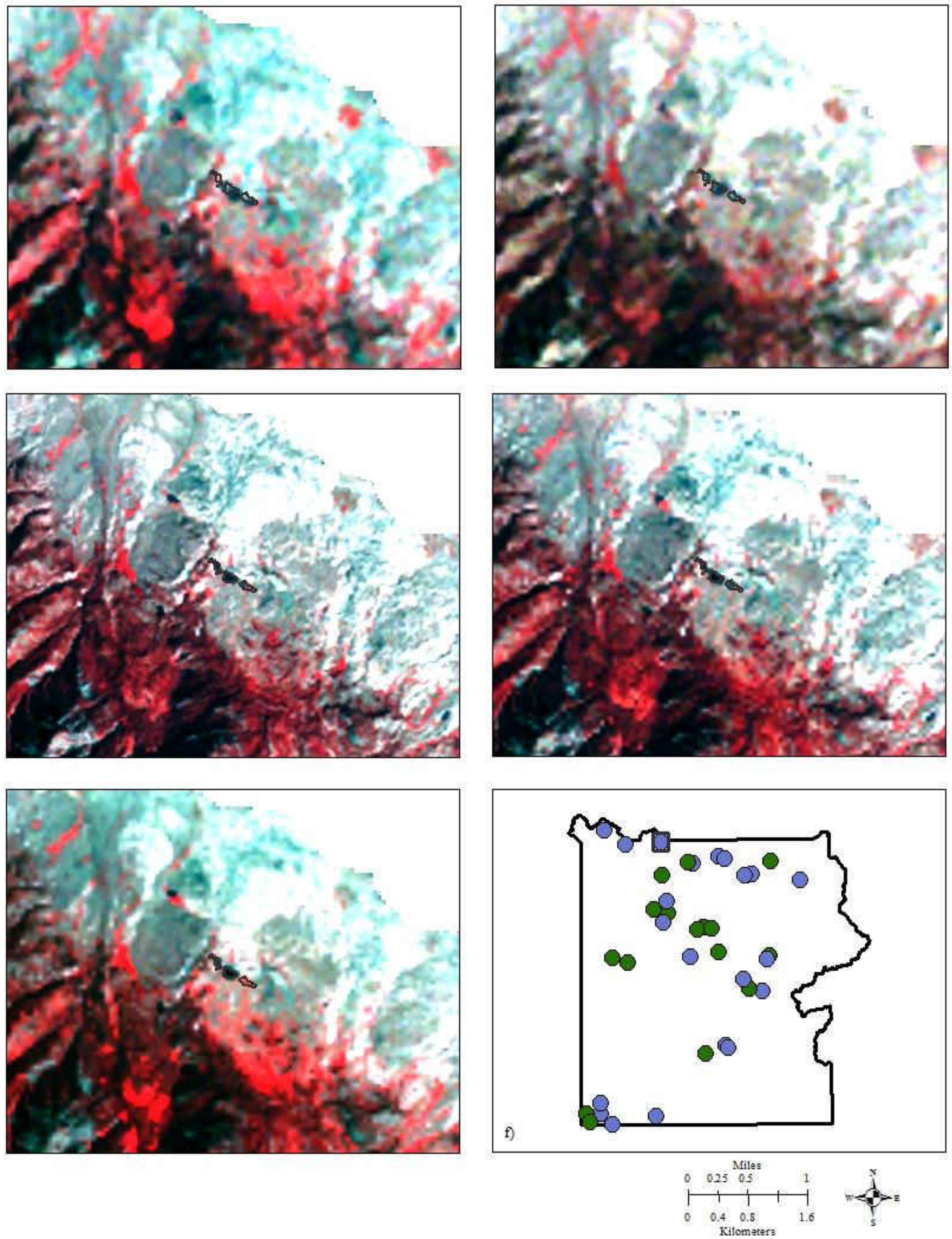

Figure 39. Landsat image of the Rainbow Lakes historical nesting site.

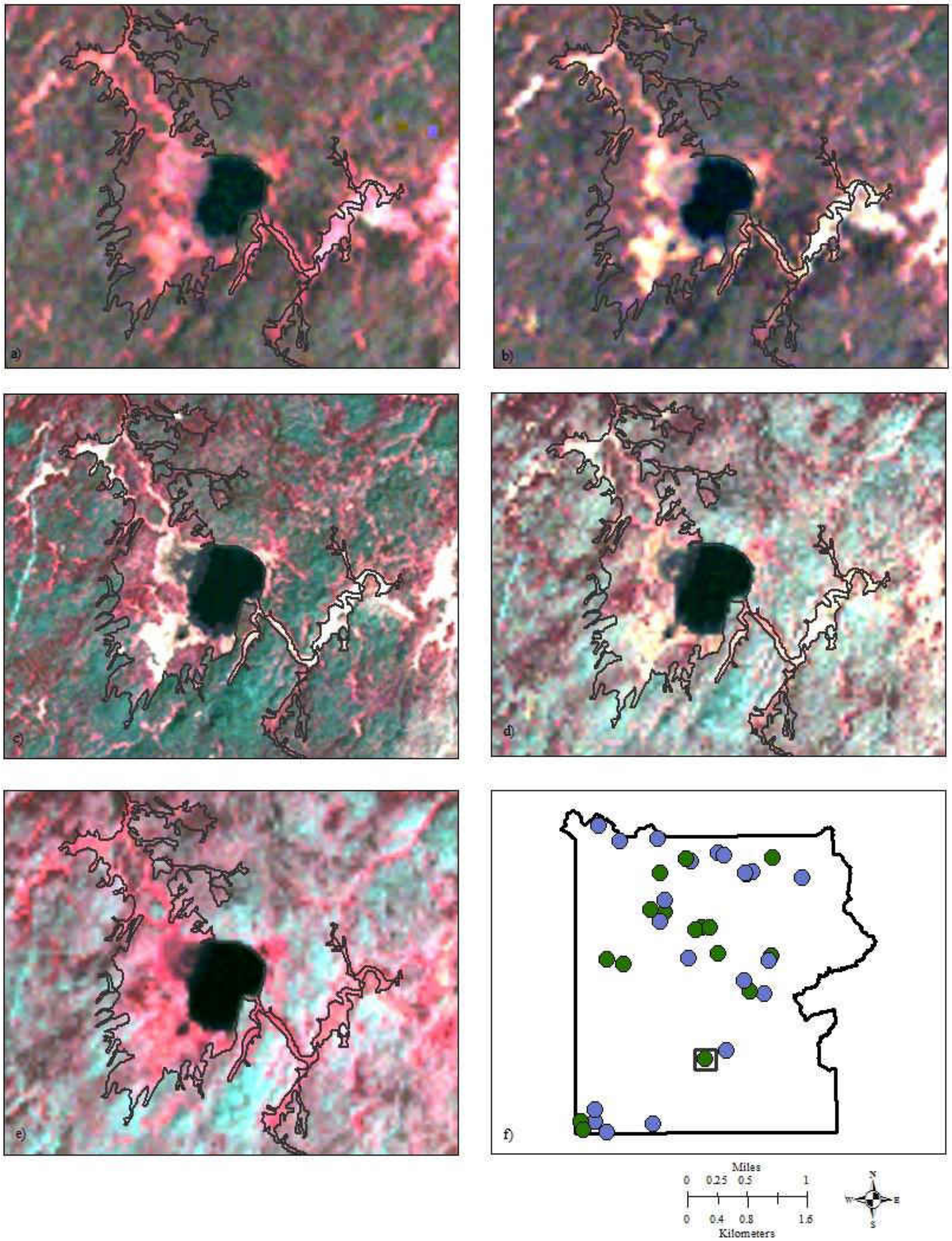

Figure 40. Landsat image of the Riddle Lake historical nesting site.

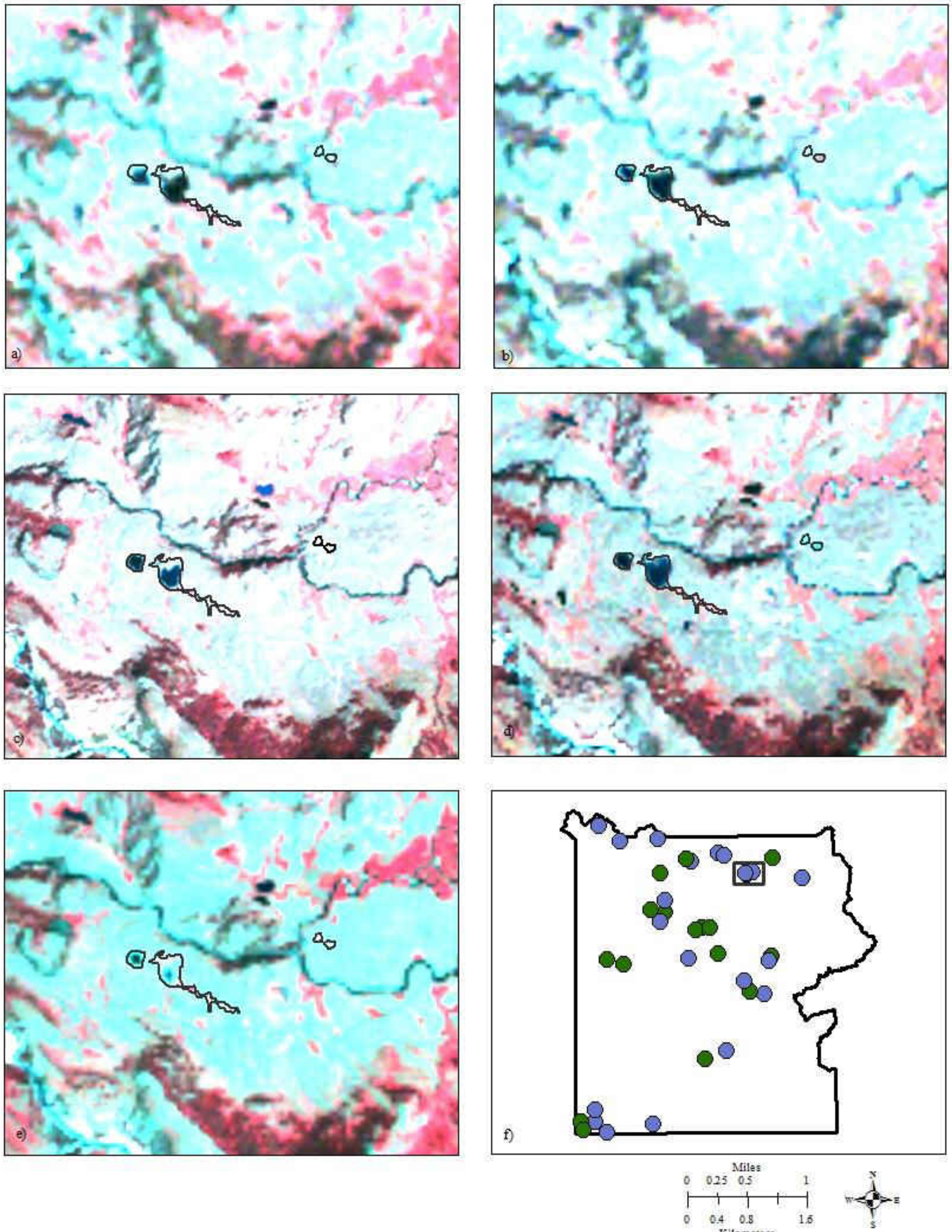

Figure 41. Landsat image of the Slough Creek Ponds and Trumpeter Lakes historical nesting sites.

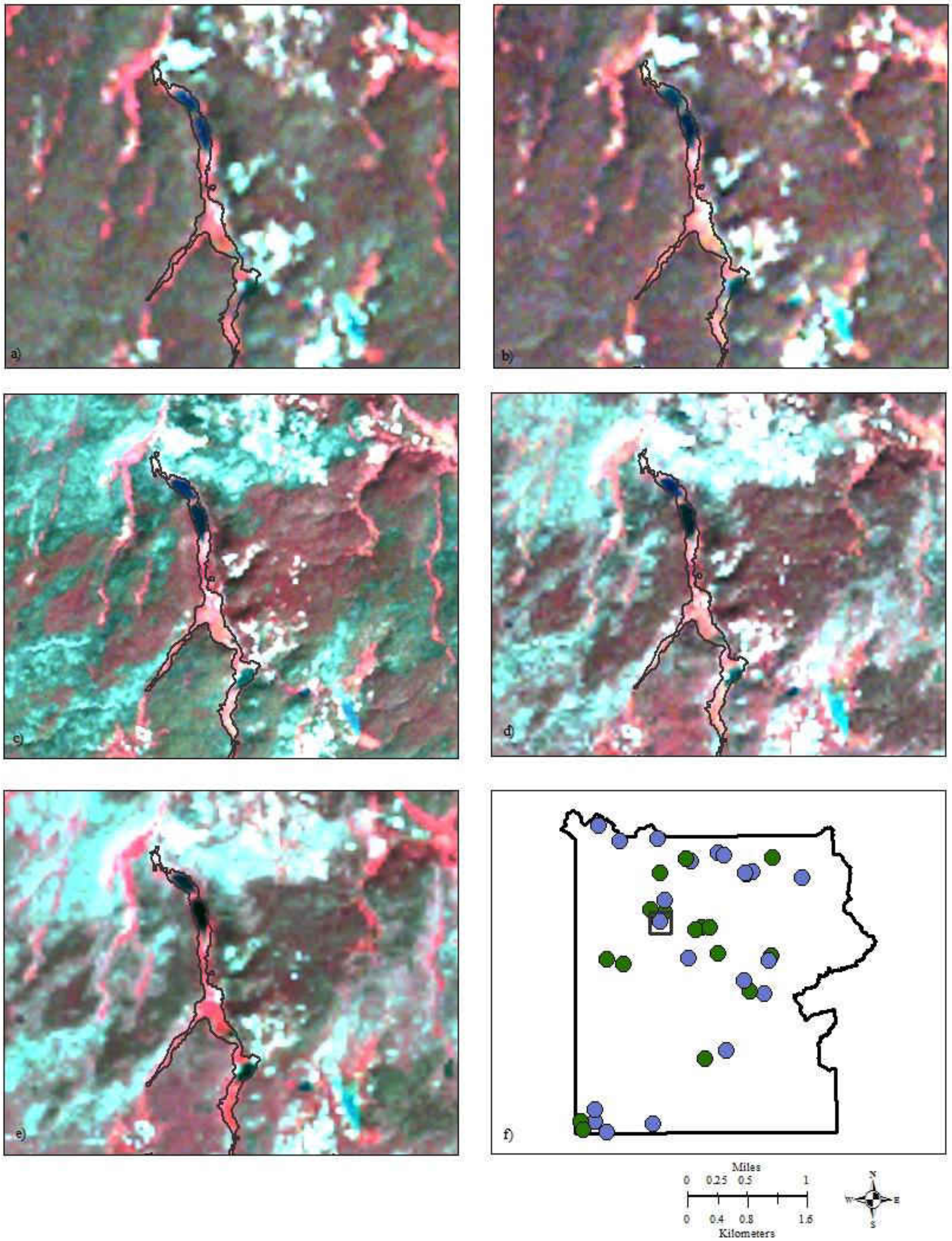

Figure 42. Landsat image of the South Twin Lake historical nesting site.

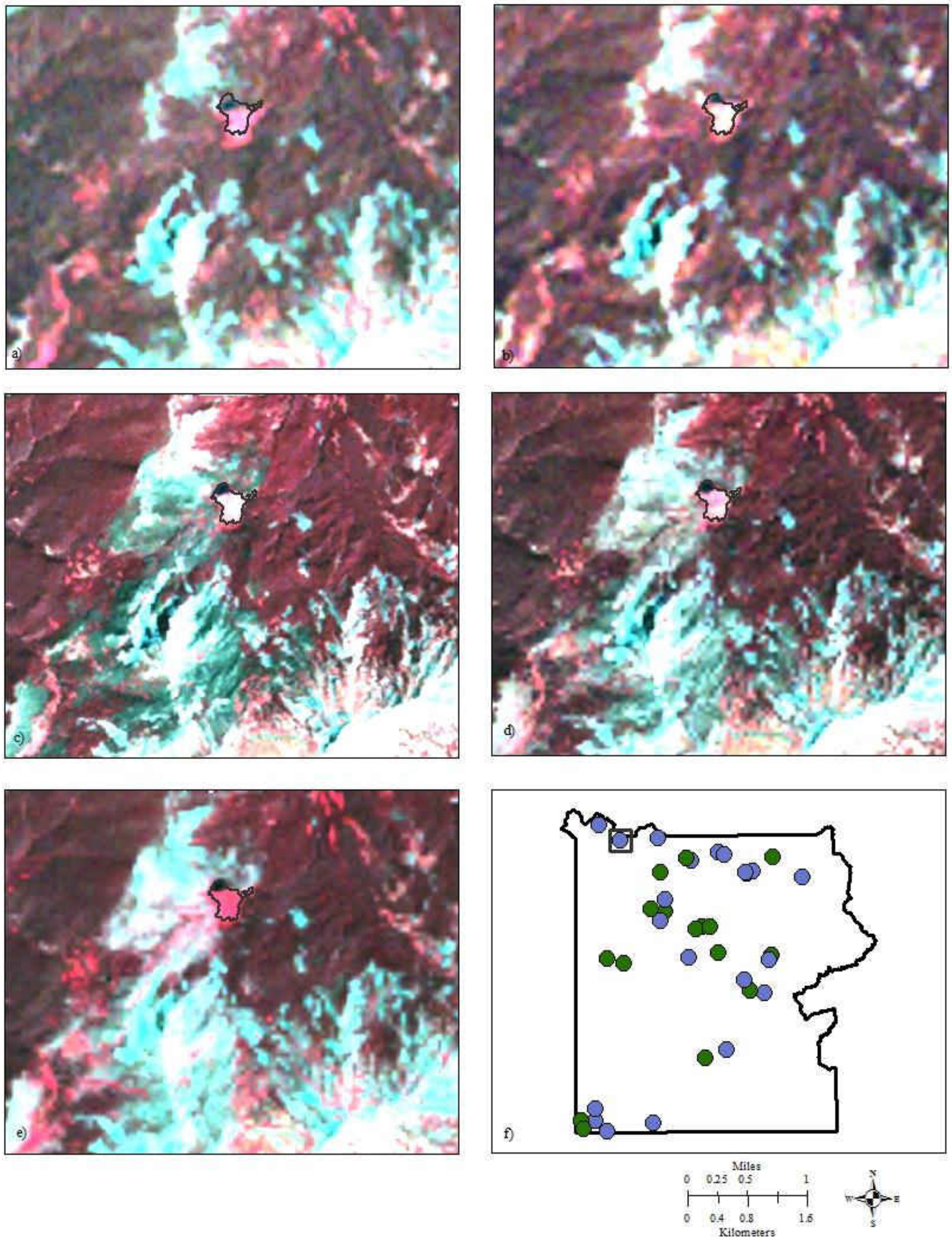

Figure 43. Landsat image of the Sportsman Lake historical nesting site.

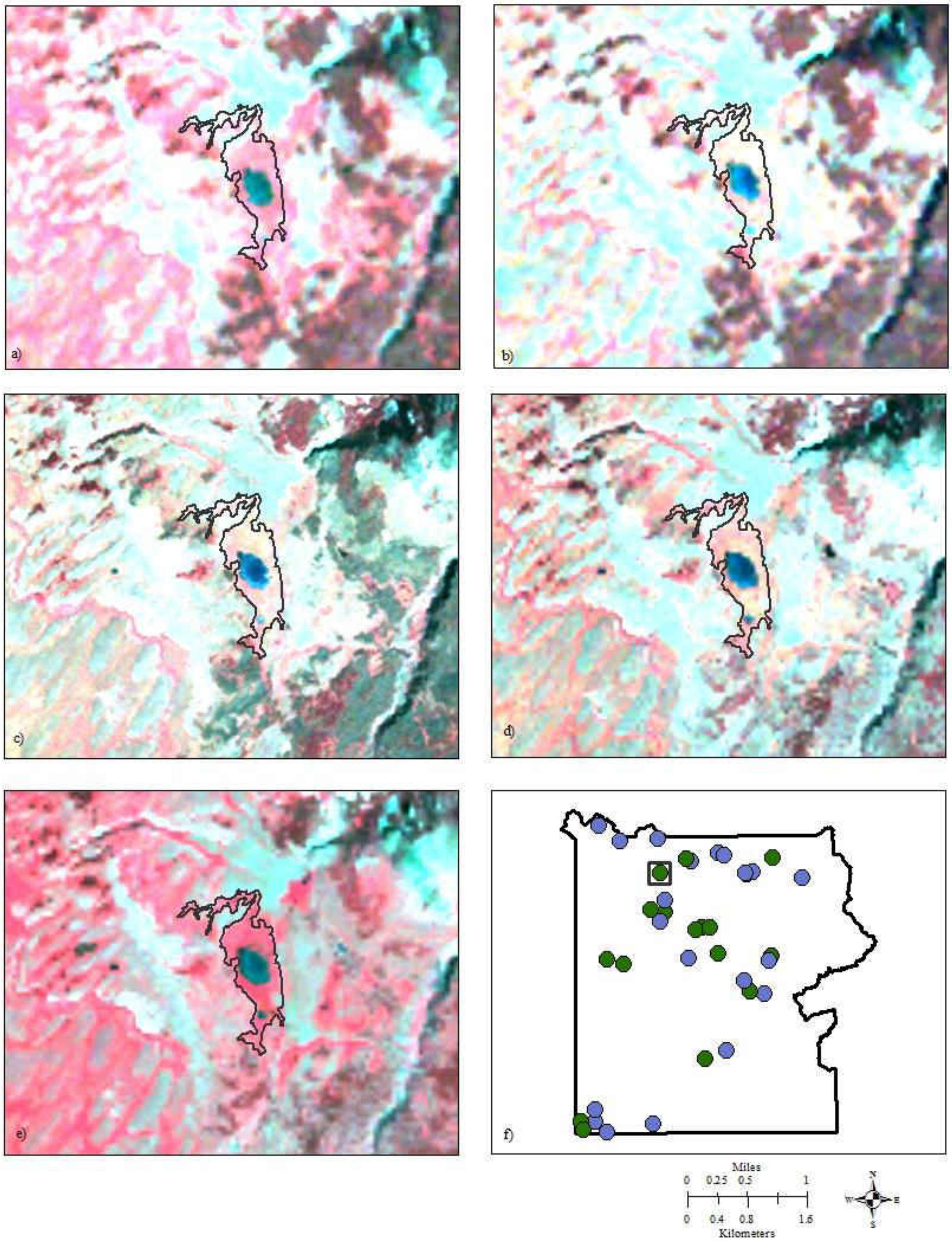

Figure 44. Landsat image of the Swan Lake historical nesting site.

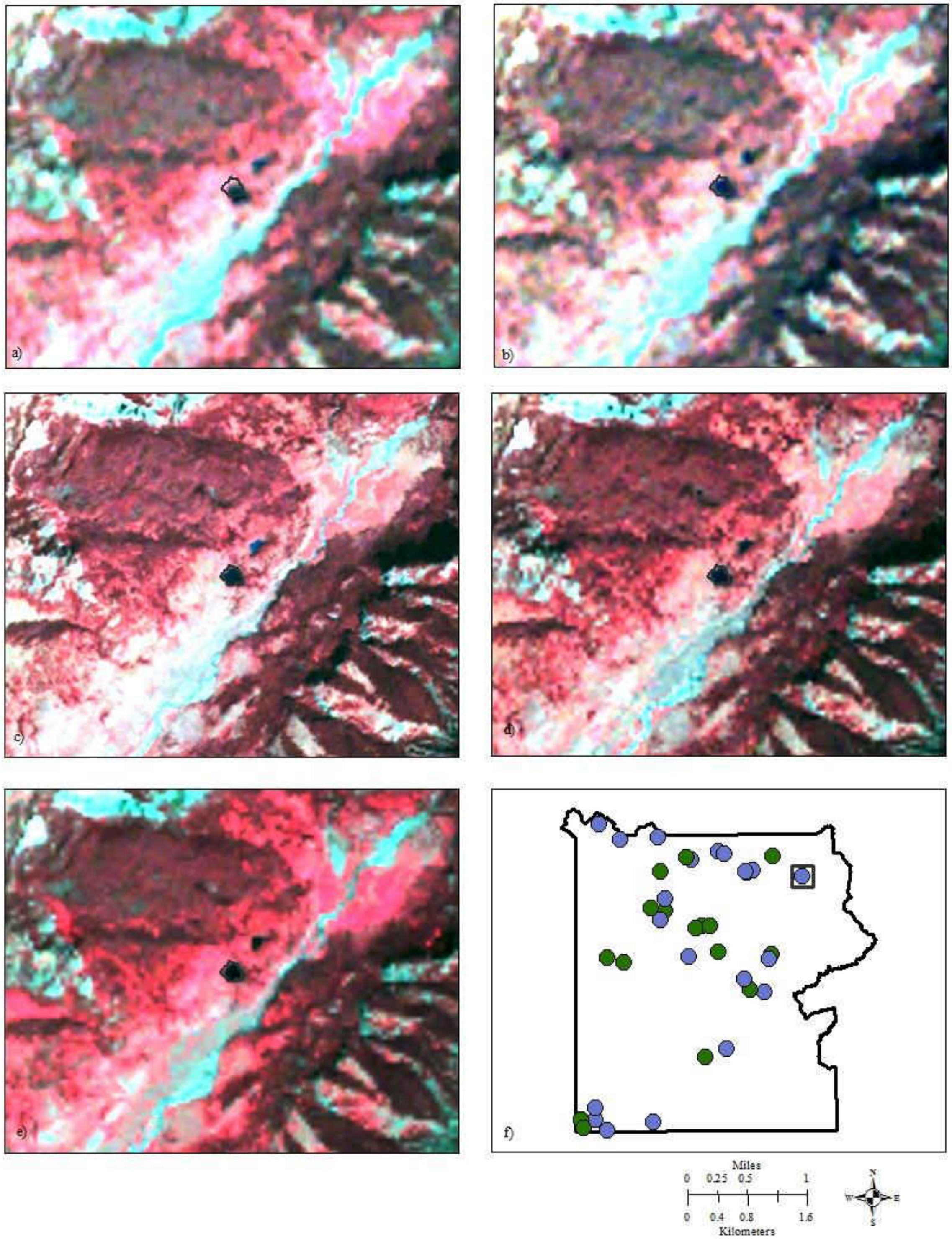

Figure 45. Landsat image of the Trout Lake historical nesting site.

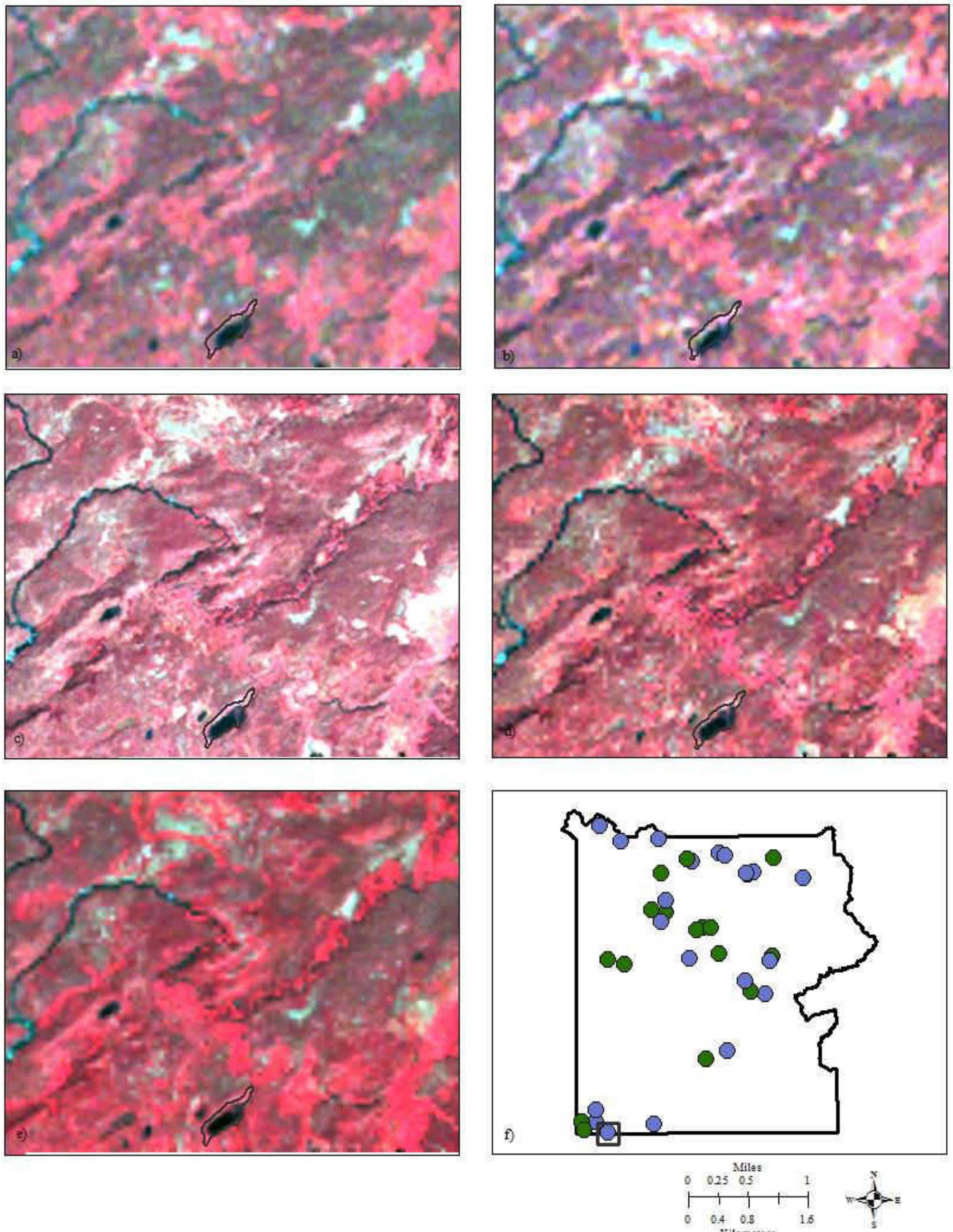

Figure 46. Landsat image of the Winegar Lake historical nesting site.

APPENDIX D:

NDVI IMAGES

Viewer-subjective evaluations utilized NDVI images which were calculated using the Image Analysis function. The MSS images (1975 and 1979) were calculated using band 2 as the red band and band 3 as the infrared band while the TM and ETM+ images (1990, 1999, and 2005) were created using band 3 as the red band and band 4 as the infrared band. Each image is displayed in a 1:60,000 scale unless otherwise noted, with the YNP image displayed at a 1:1,500,000 scale for location purposes. Sites sampled in 2009 are marked with green dots, while sites sampled in 2010 are marked with blue dots. The images are displayed, in order:

a) 1975 MSS;
b) 1979 MSS;
c) 1990 TM;
d) 1999 ETM+;
e) 2005 ETM+;
f) YNP location map.

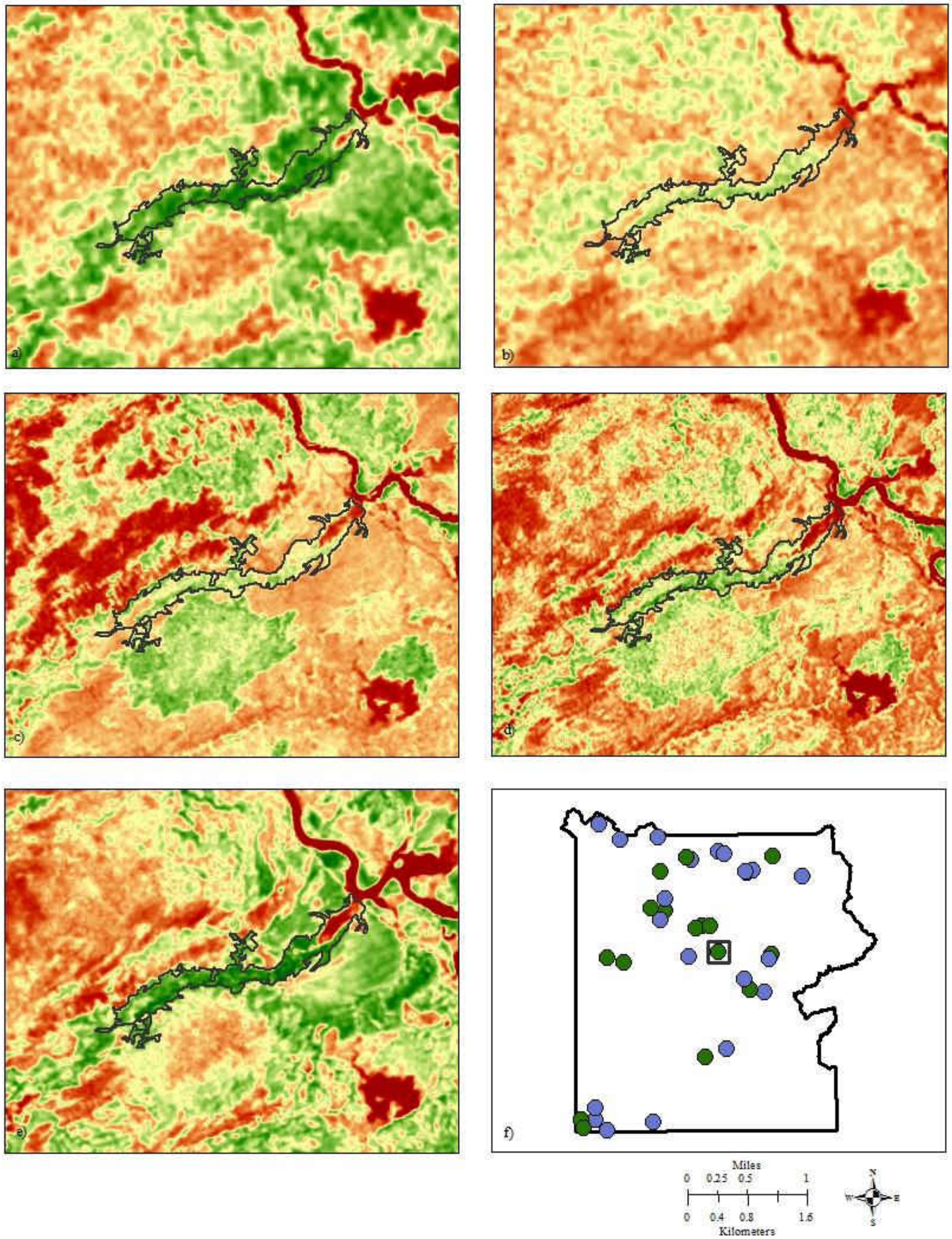

Figure 47. NDVI image of the Alum Creek historical nesting site.

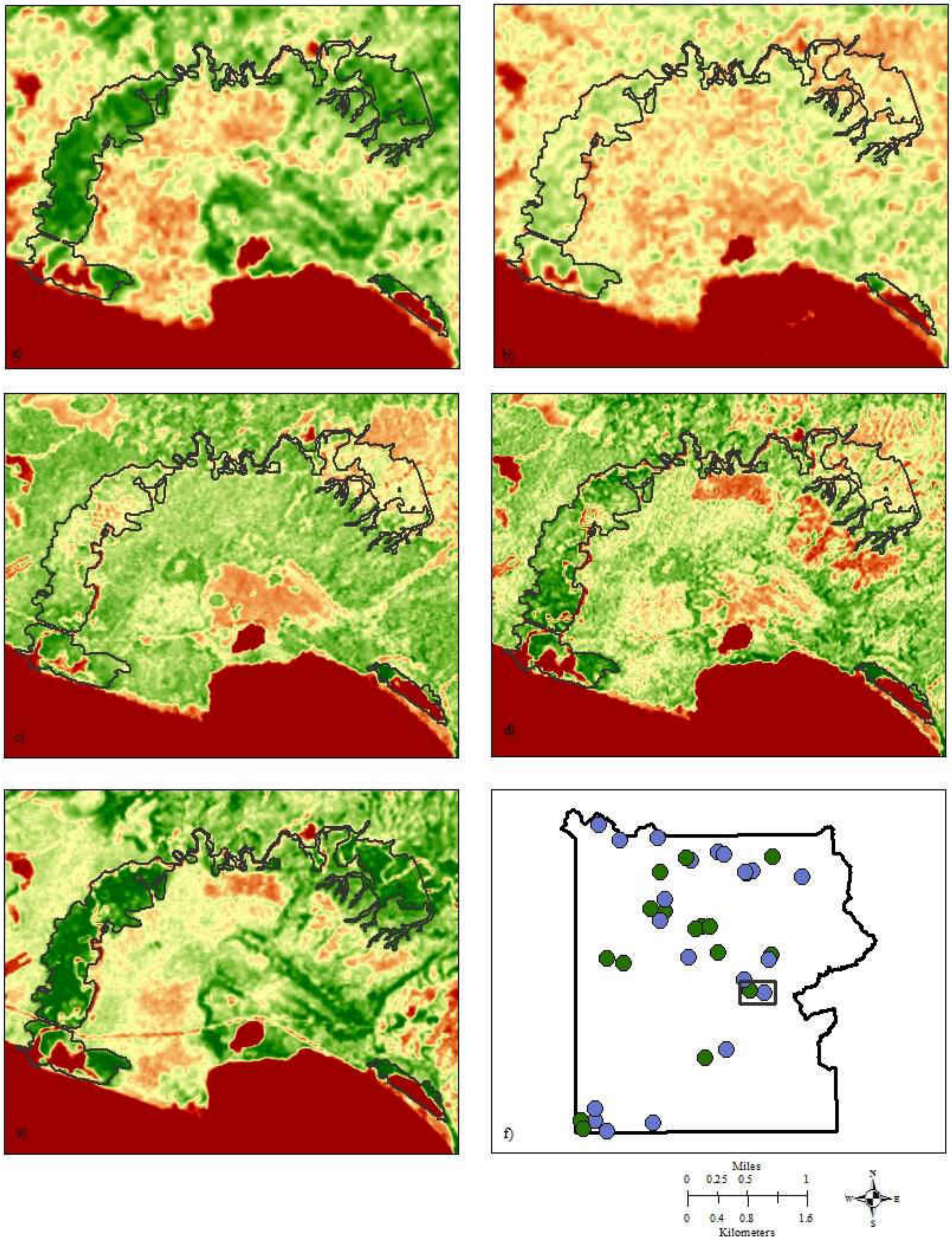

Figure 48. NDVI image of the Beach Springs Lagoon and Pelican Creek historical nesting sites.

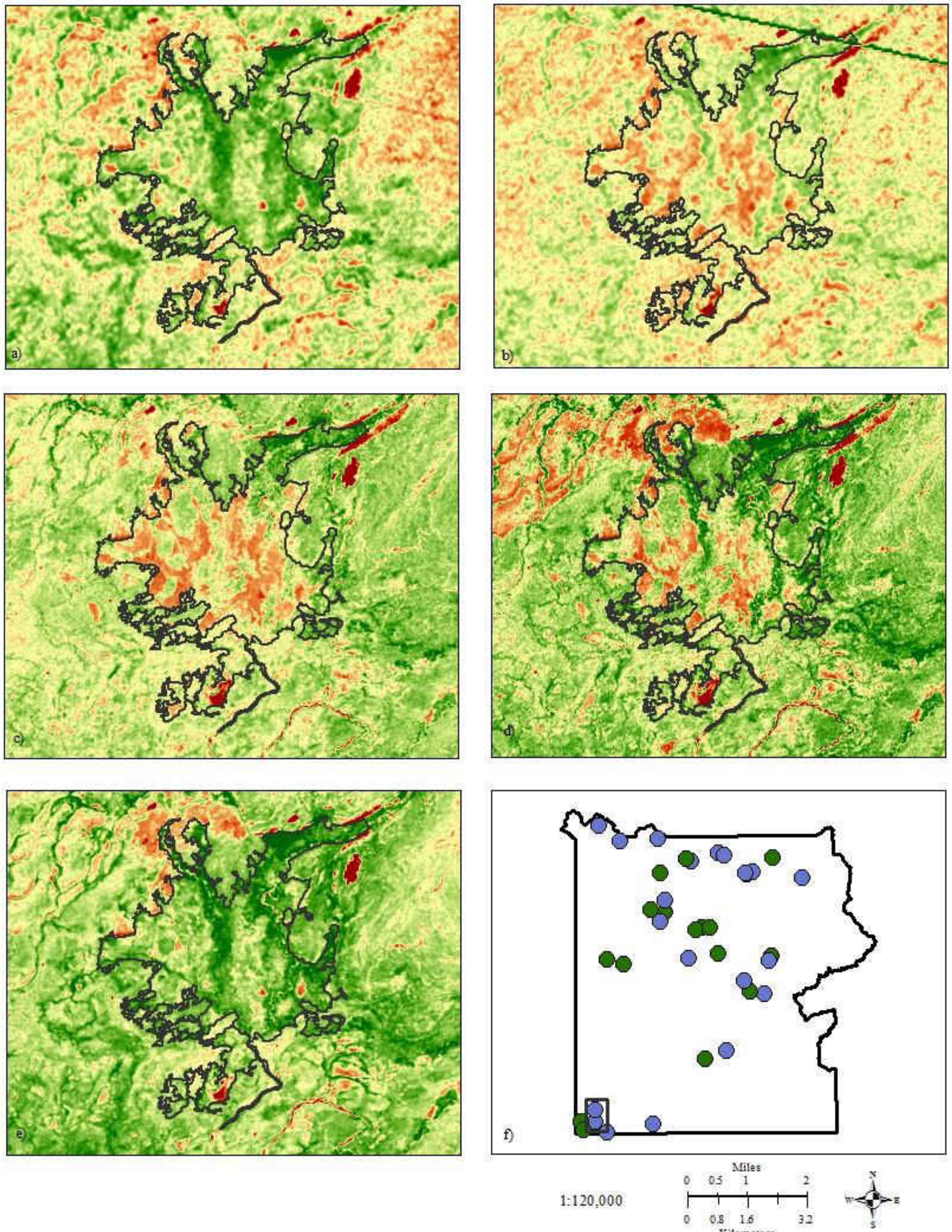

Figure 49. NDVI image of the Bechler Meadows and Lilypad Lake historical nesting sites.

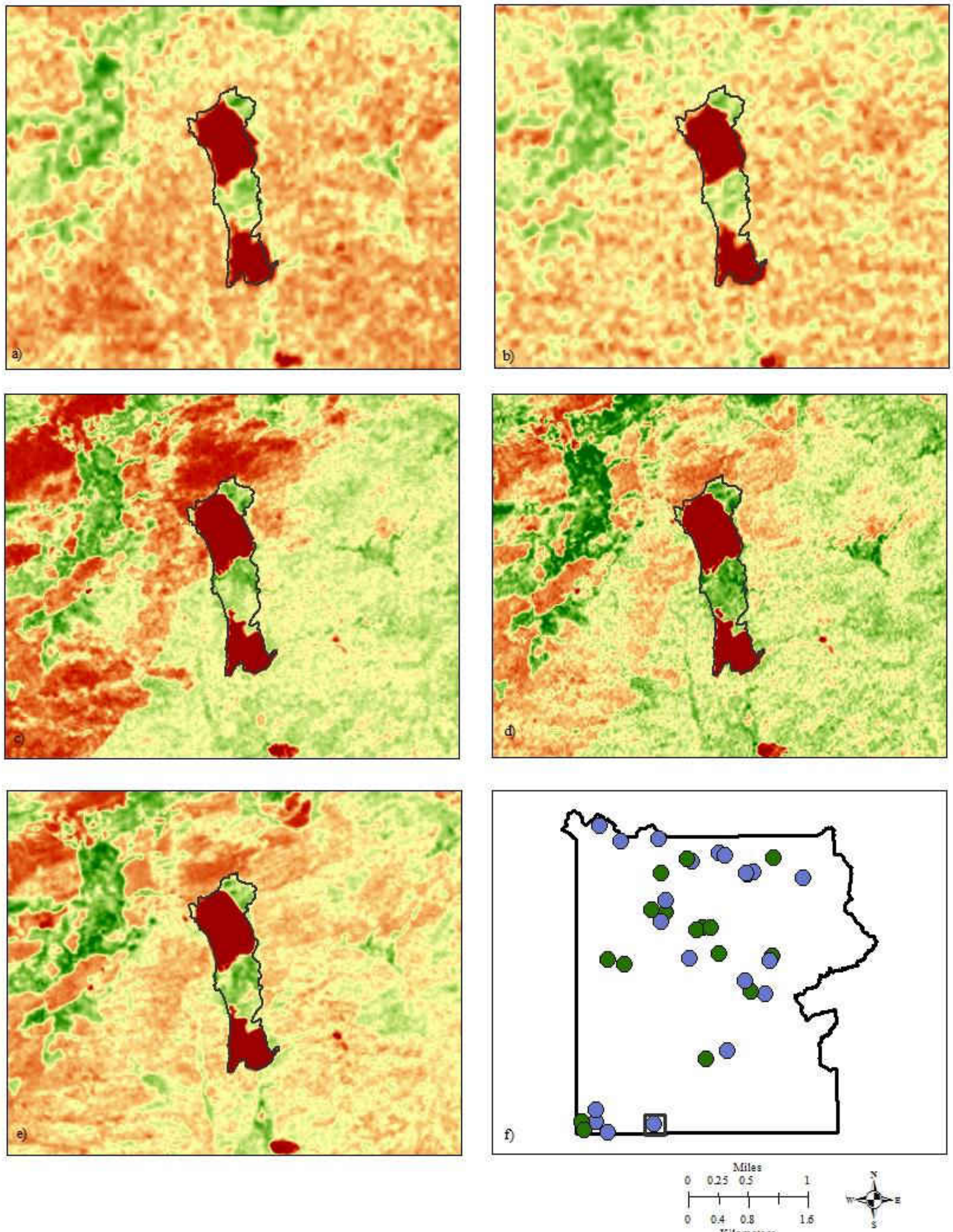

Figure 50. NDVI image of the Beula Lake historical nesting site.

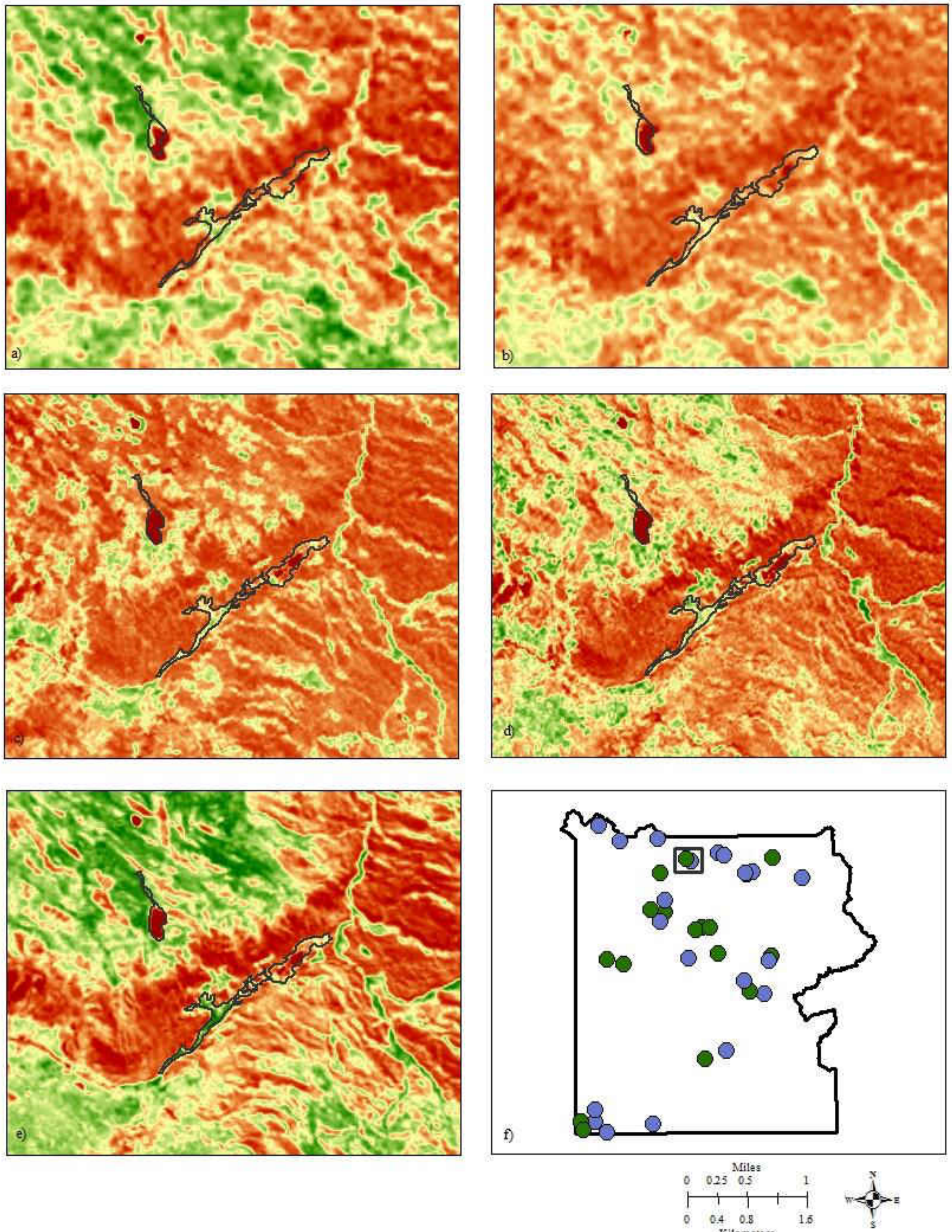

Figure 51. NDVI image of the Blacktail Ponds and Mount Everts Lake historical nesting sites.

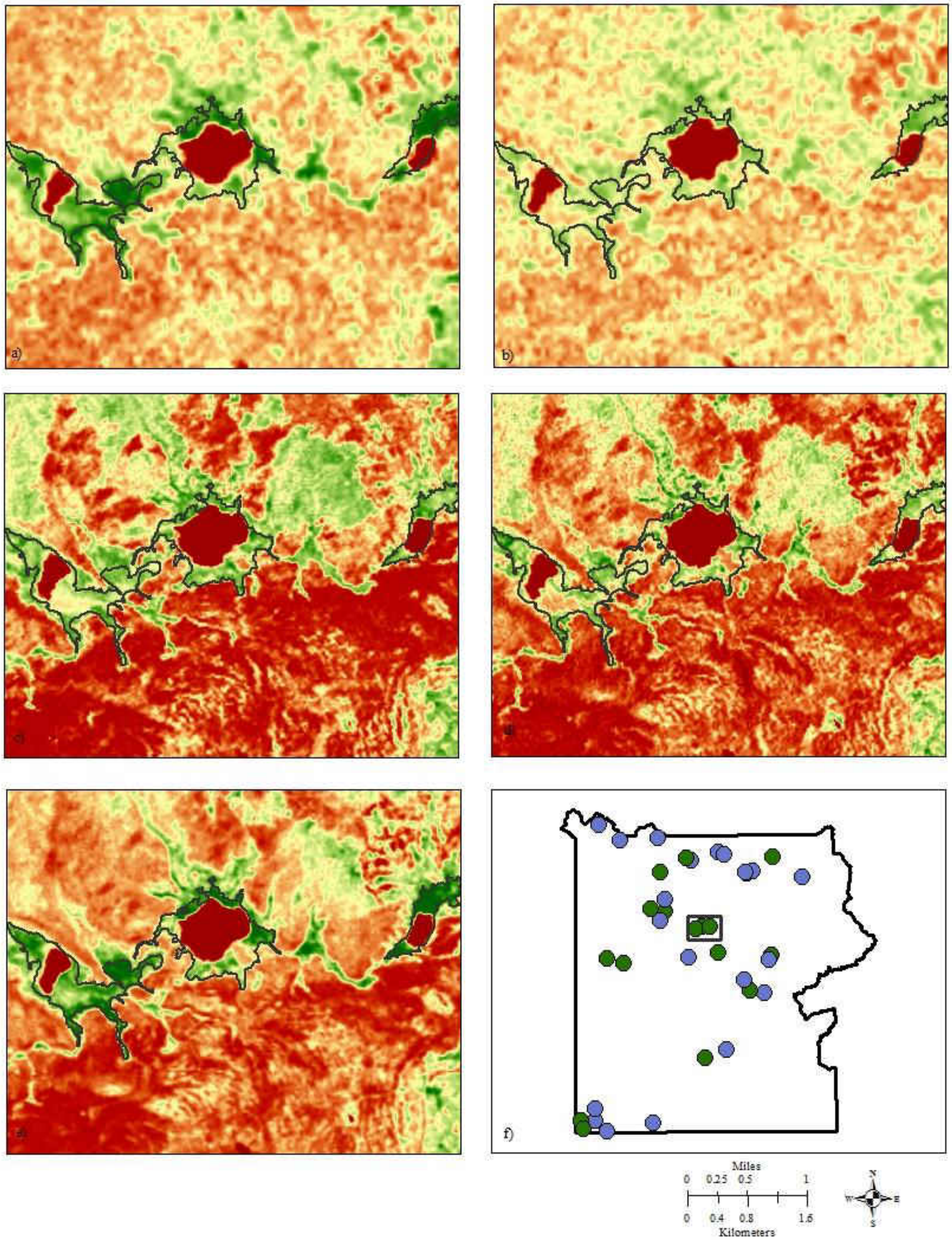

Figure 52. NDVI image of the Cascade Lake, Grebe Lake, and Wolf Lake historical nesting sites.

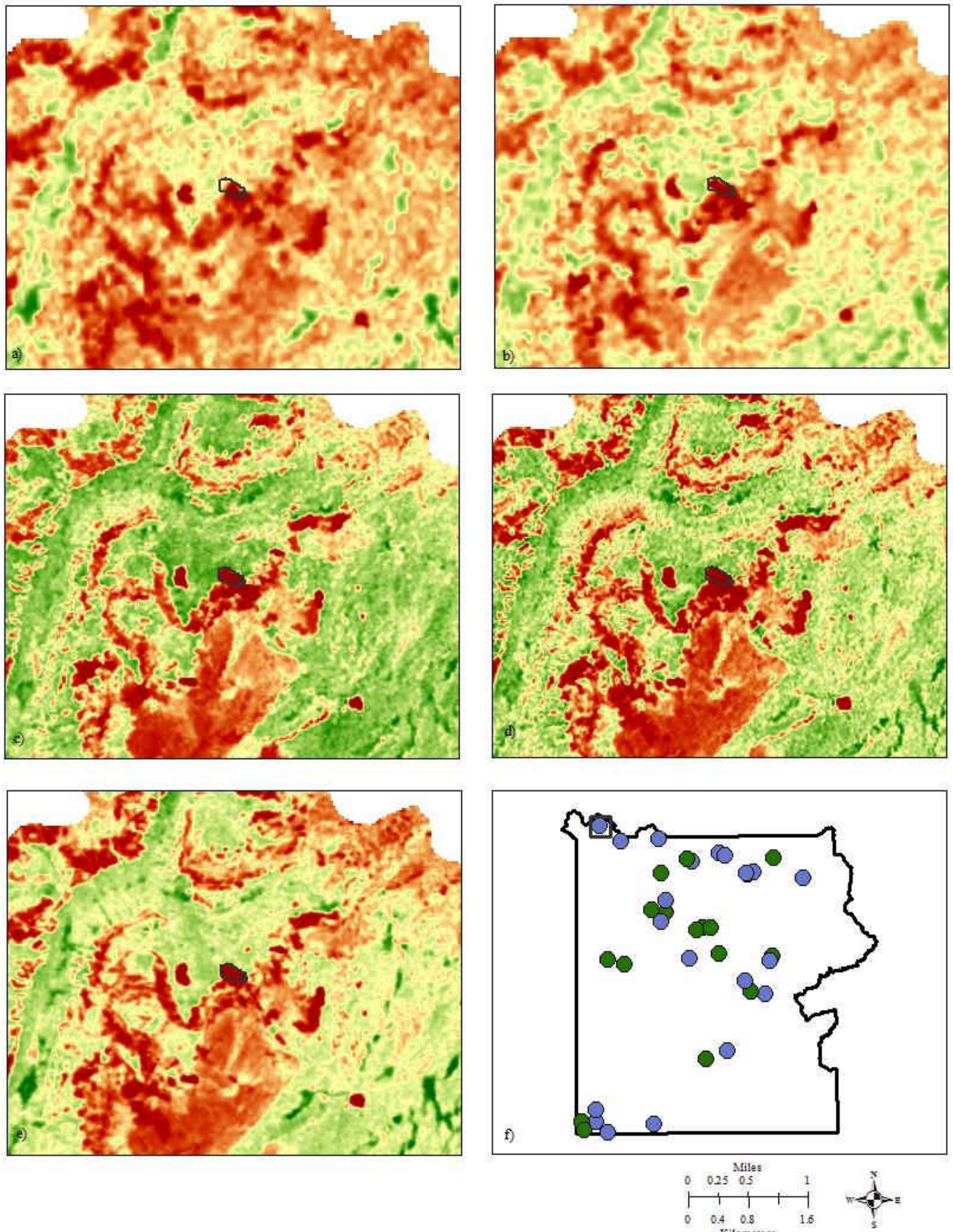

Figure 53. NDVI image of the Crescent Lake historical nesting site.

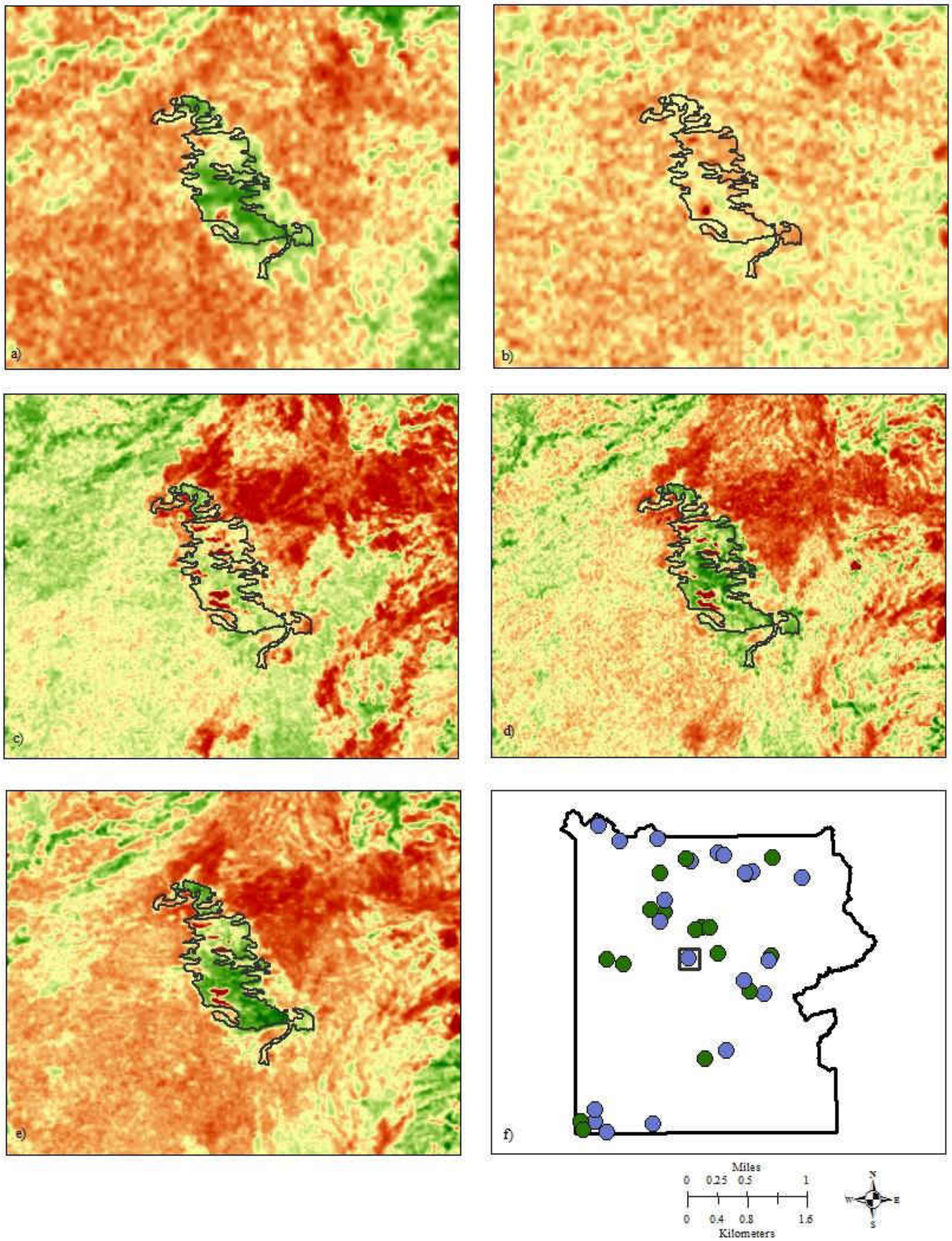

Figure 54. NDVI image of the Cygnet Lakes historical nesting site.

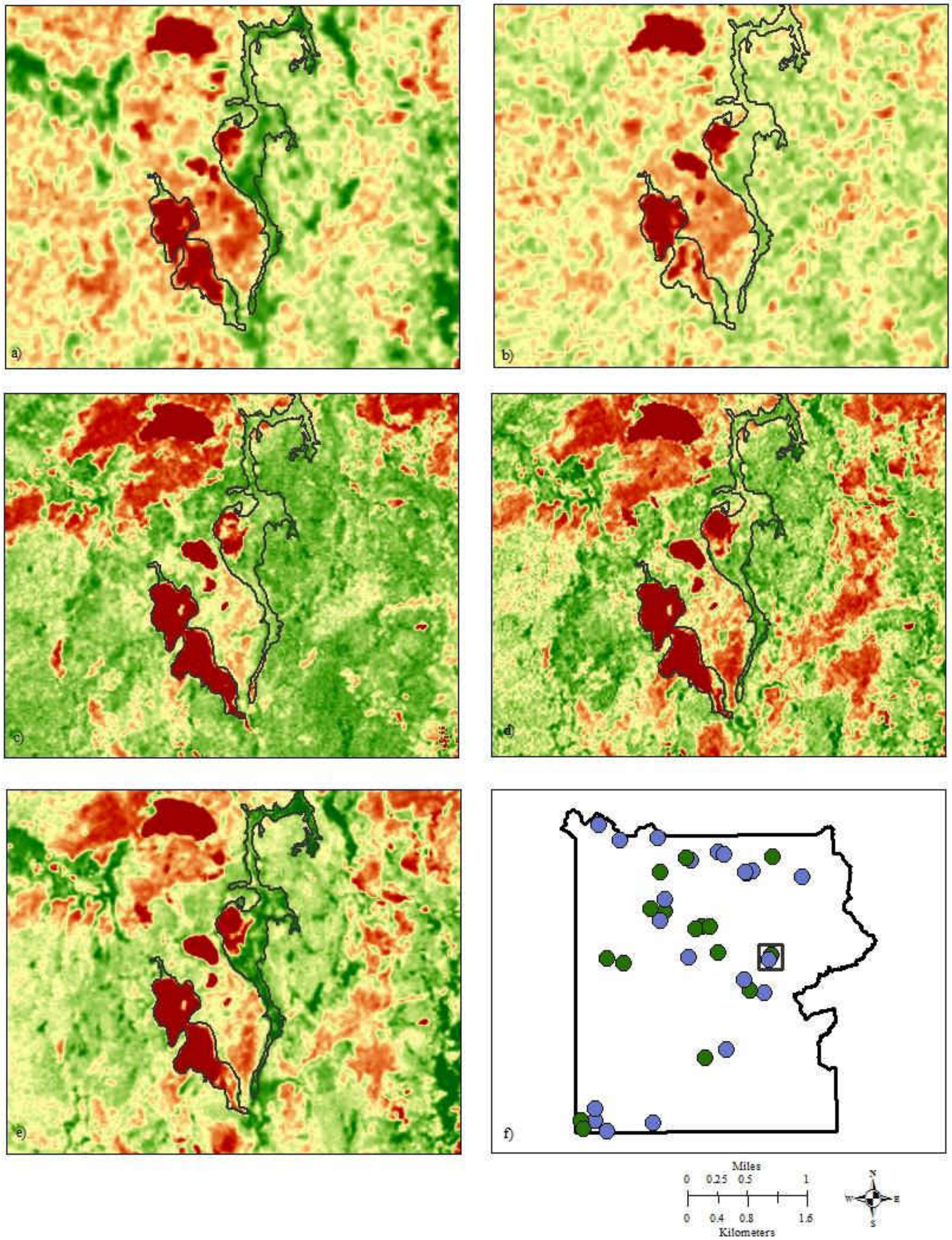

Figure 55. NDVI image of the East Tern Lake and White Lake historical nesting sites.

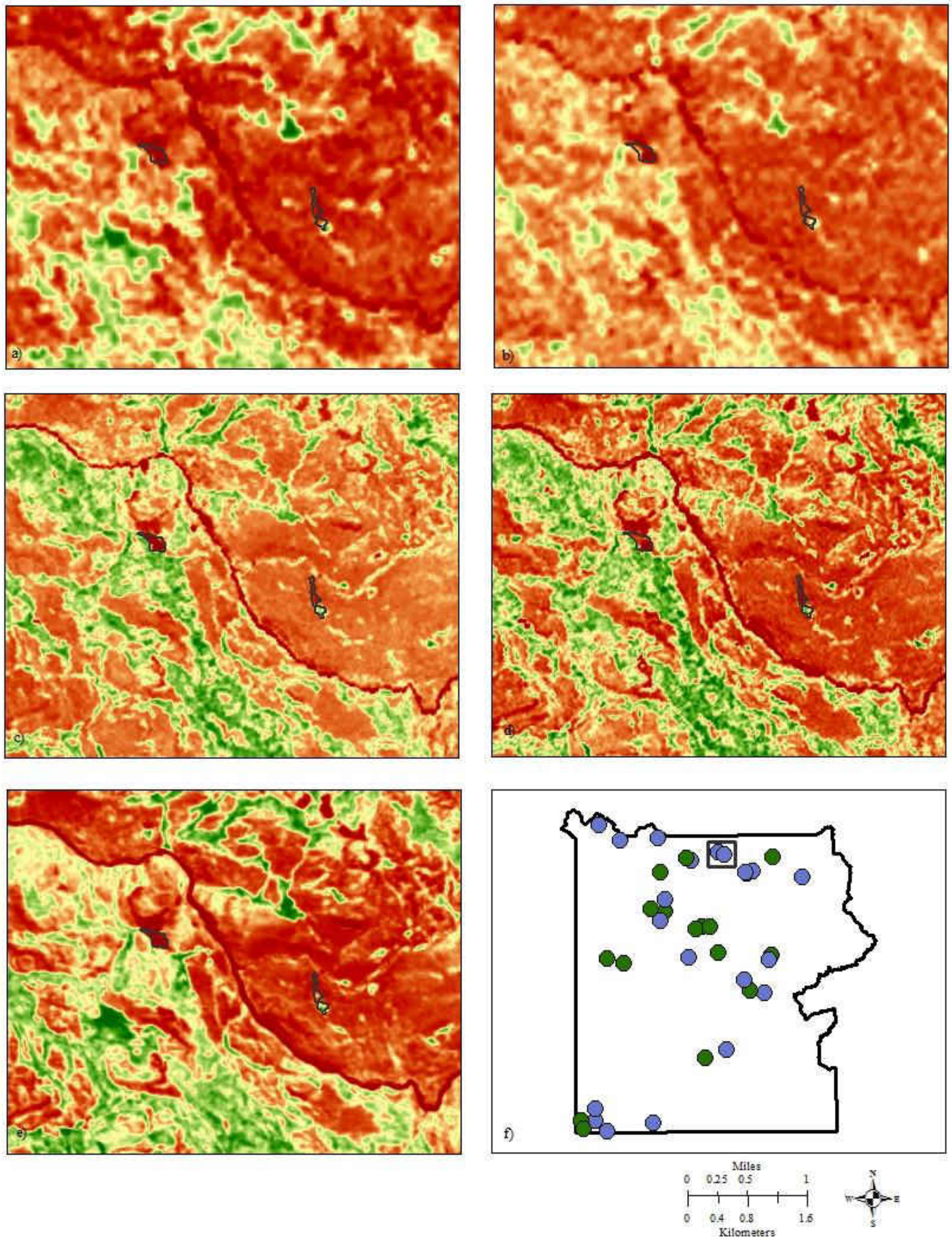

Figure 56. NDVI image of the Geode Lake and the Hellroaring Complex historical nesting sites.

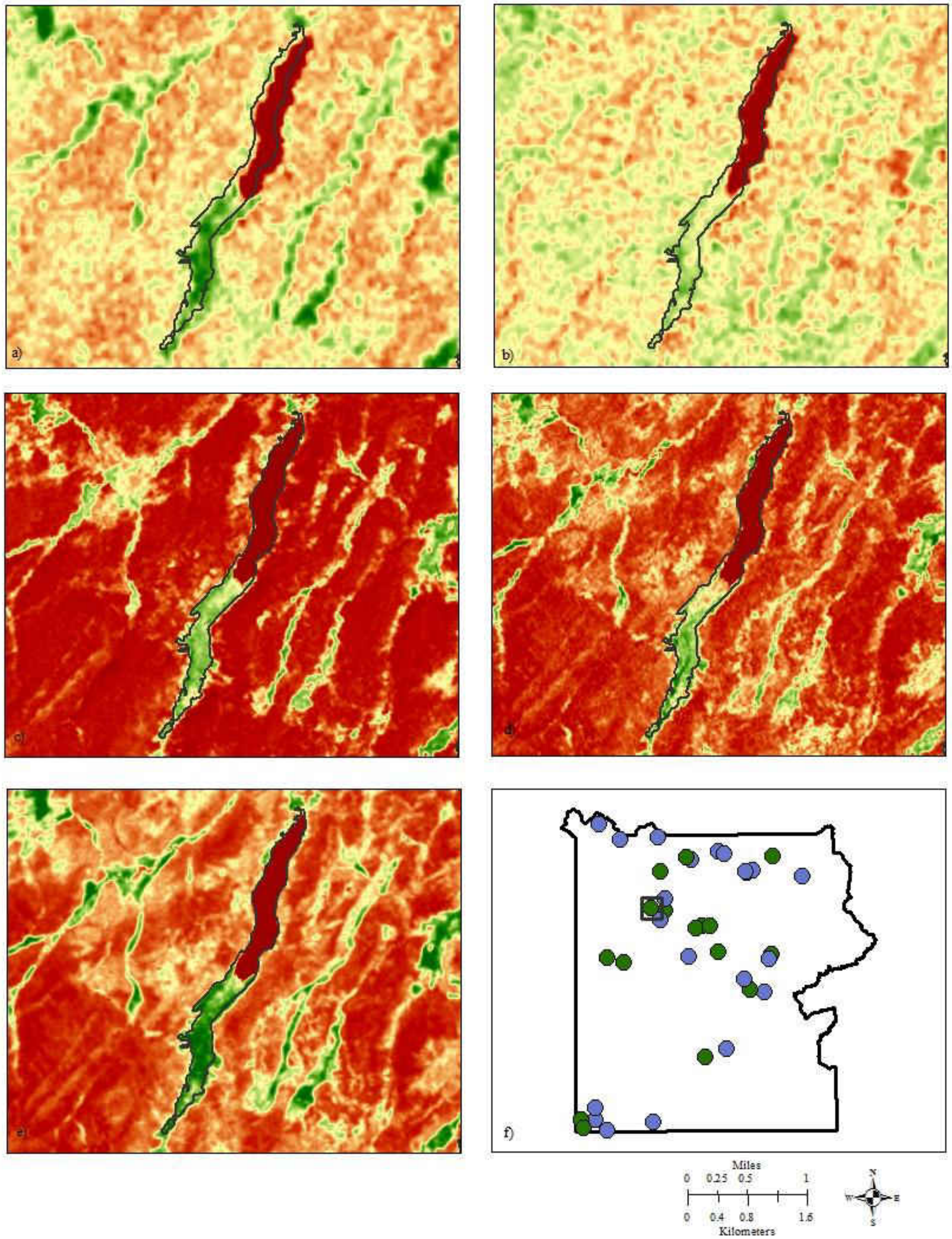

Figure 57. NDVI image of the Grizzly Lake historical nesting site.

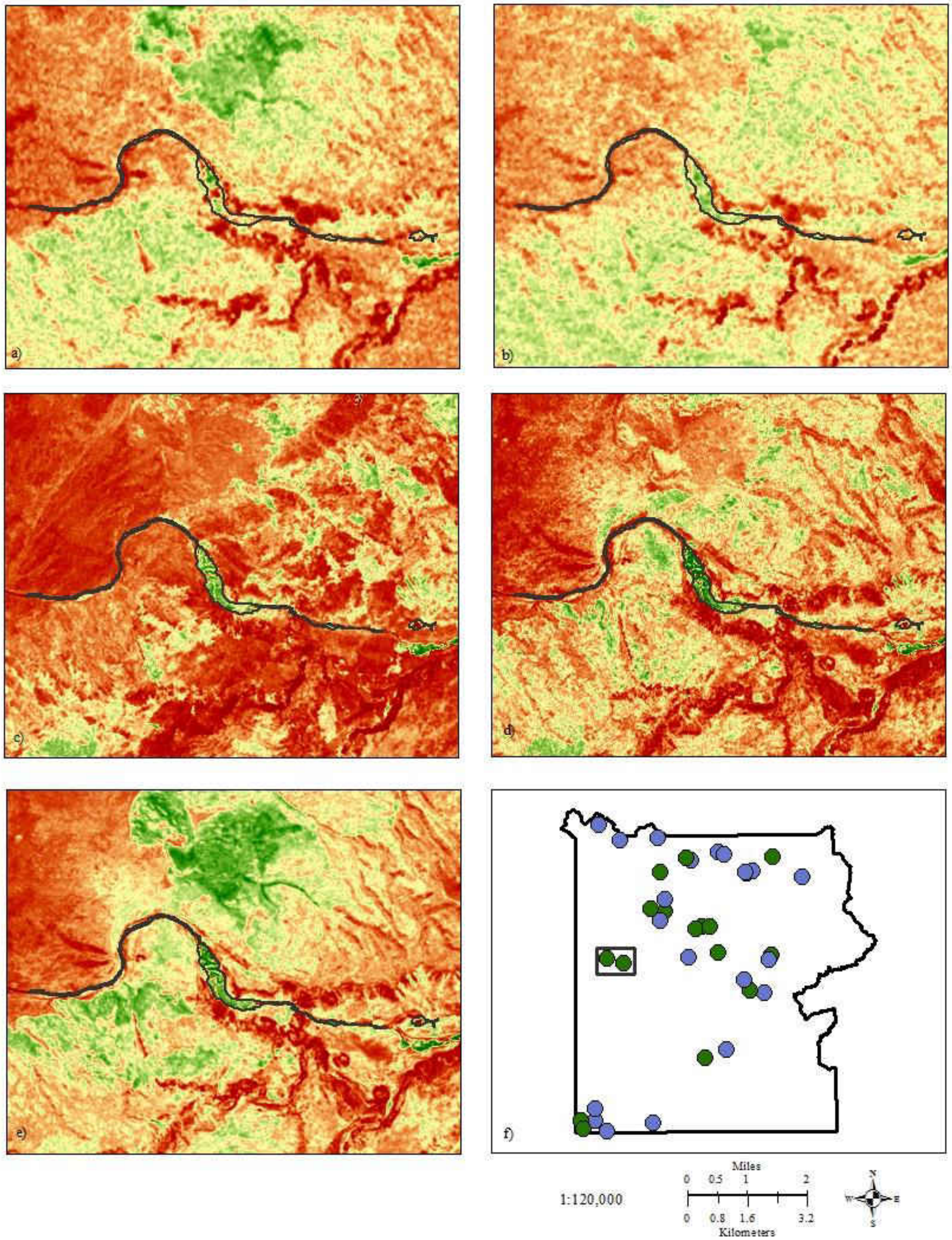

Figure 58. NDVI image of the Harlequin Lake and Seven Mile Bridge historical nesting sites.

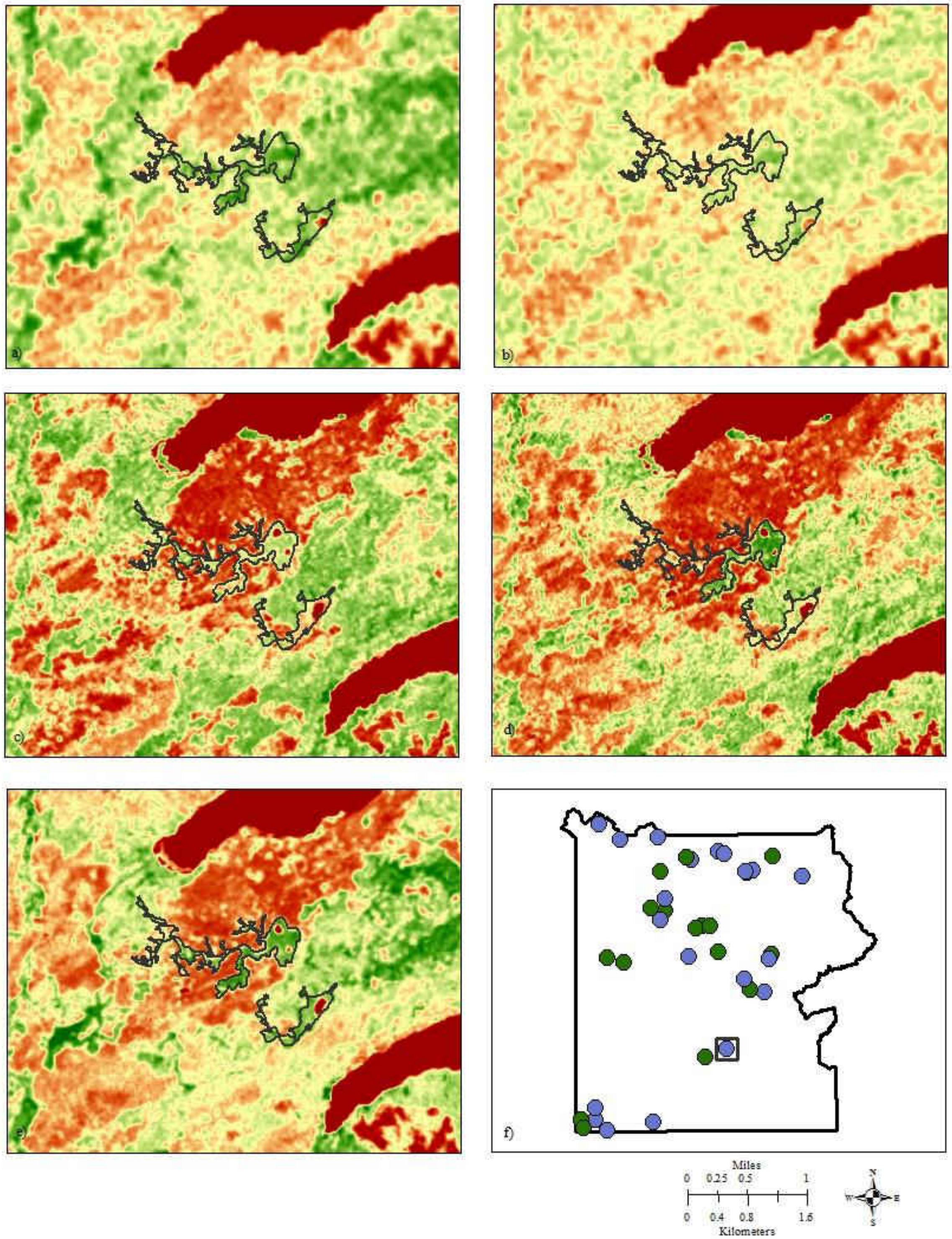

Figure 59. NDVI image of the Hidden Lakes historical nesting site.

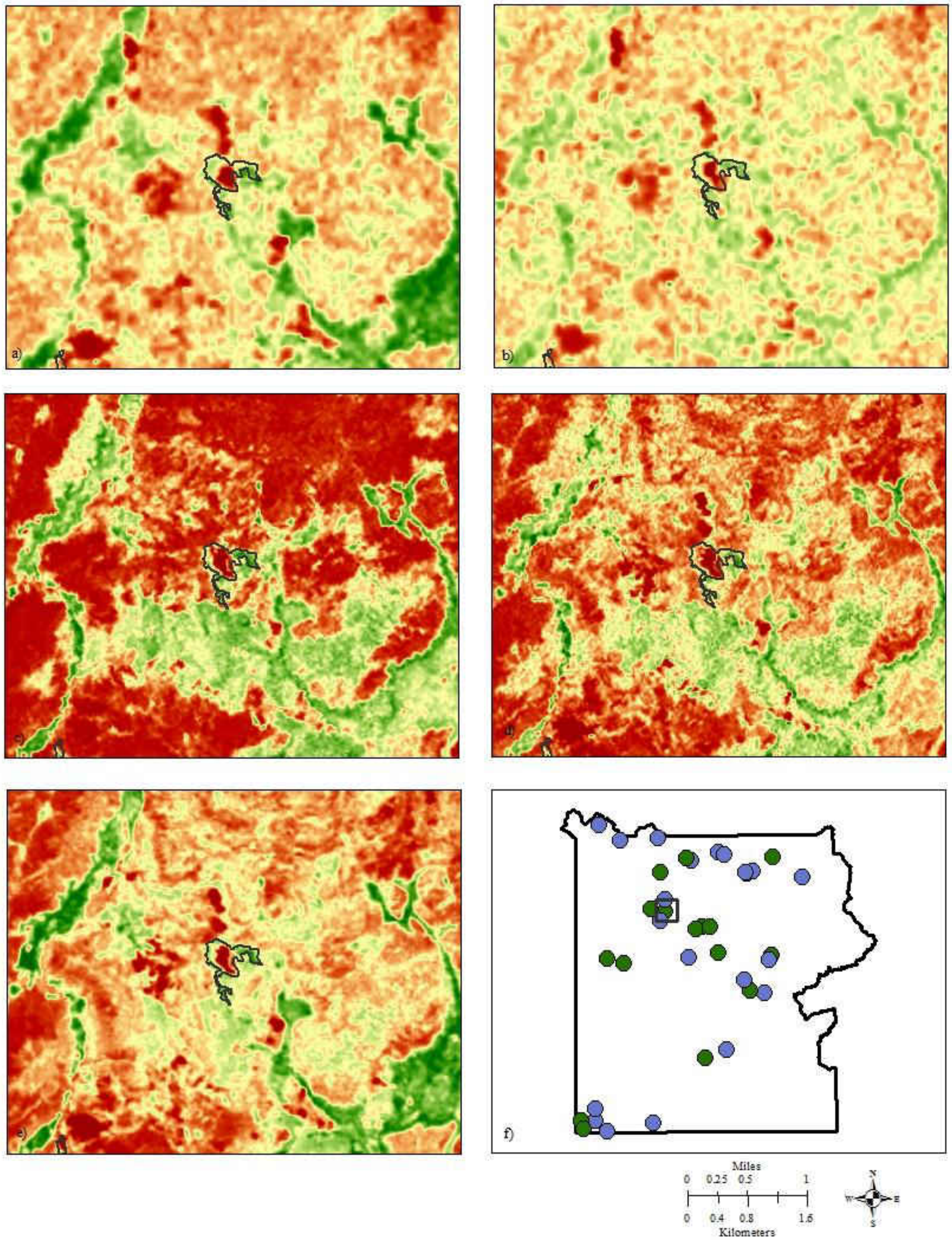

Figure 60. NDVI image of the Lake of the Woods historical nesting site.

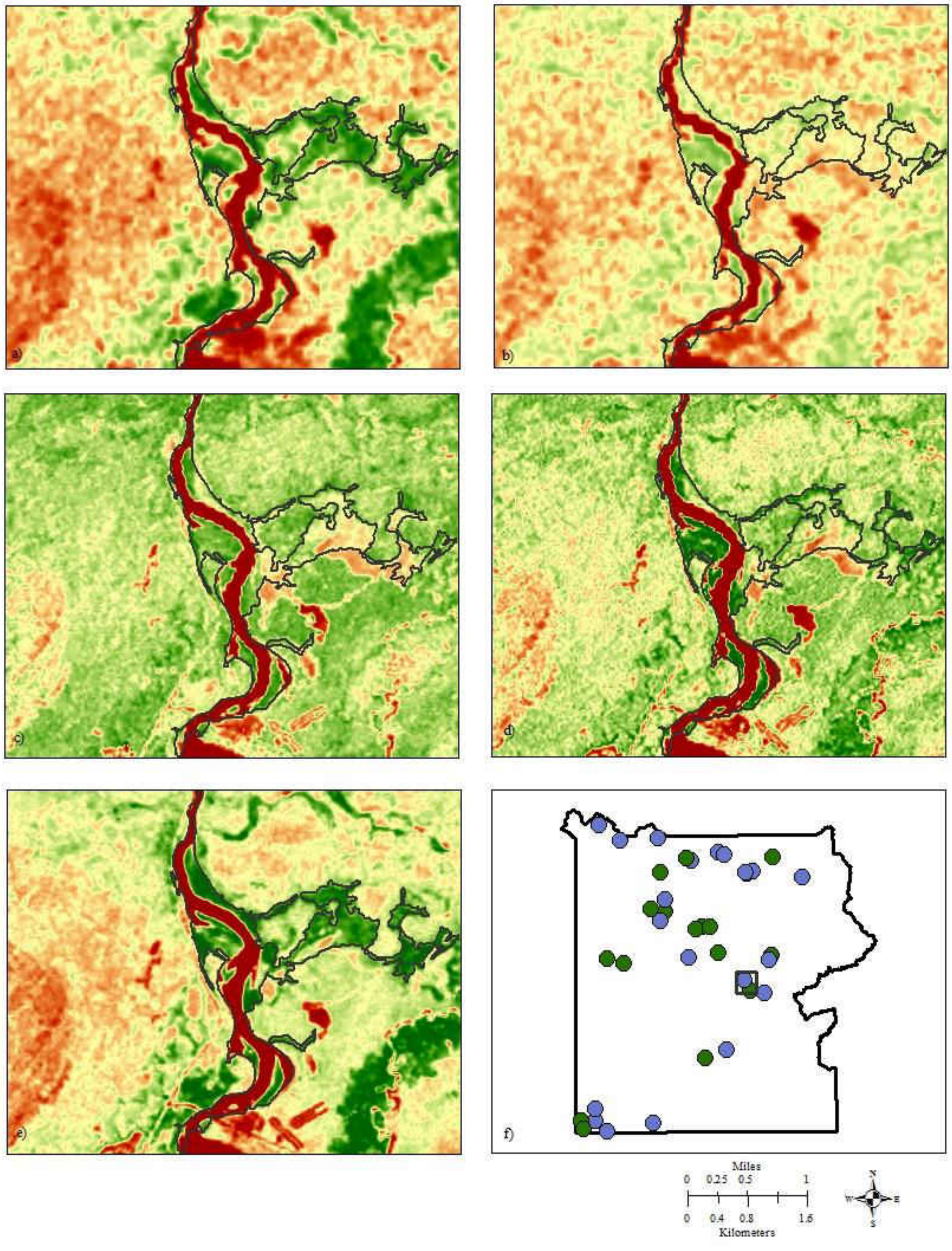

Figure 61. NDVI image of the LeHardy Rapids to Fishing Bridge historical nesting site.

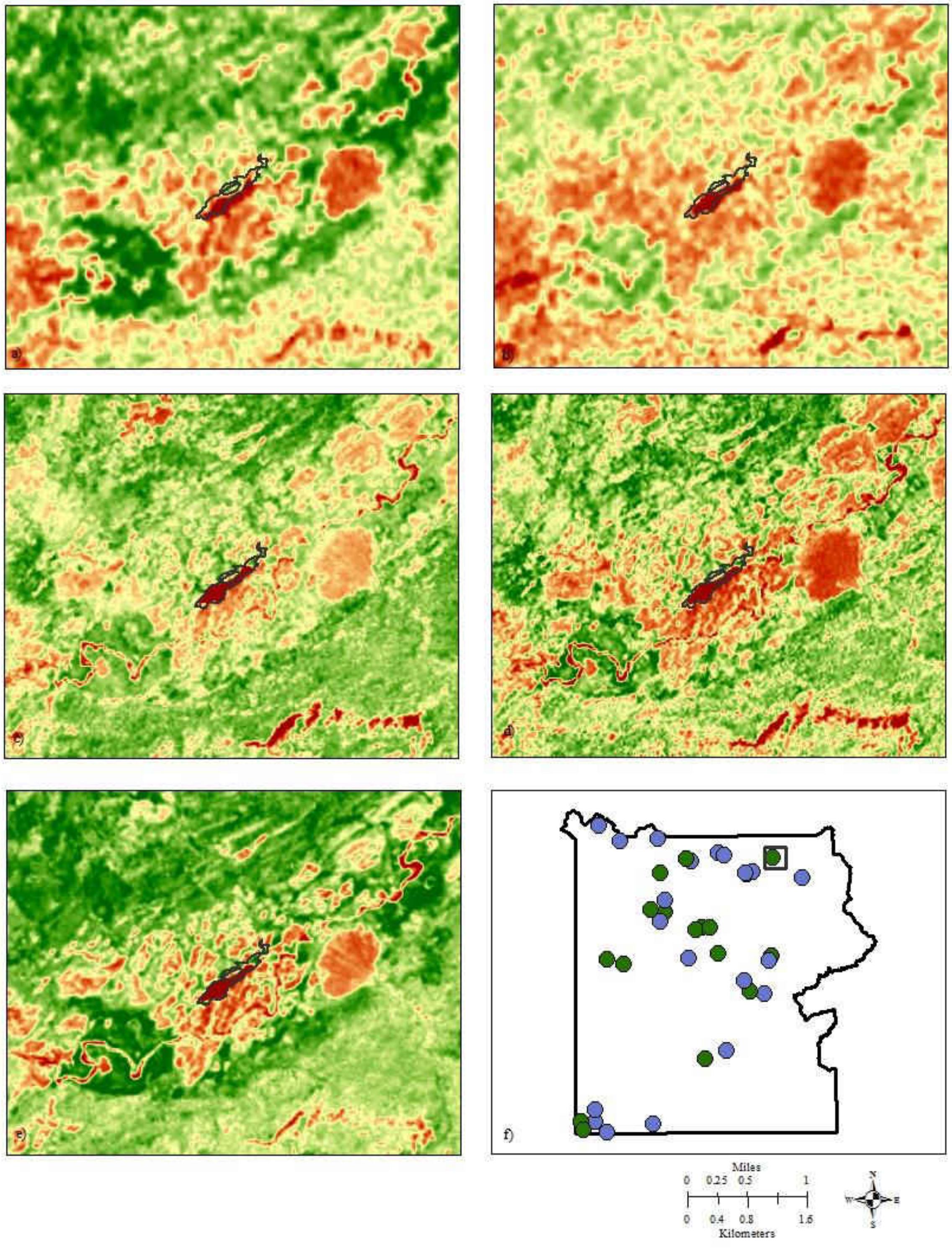

Figure 62. NDVI image of the McBride Lake historical nesting site.

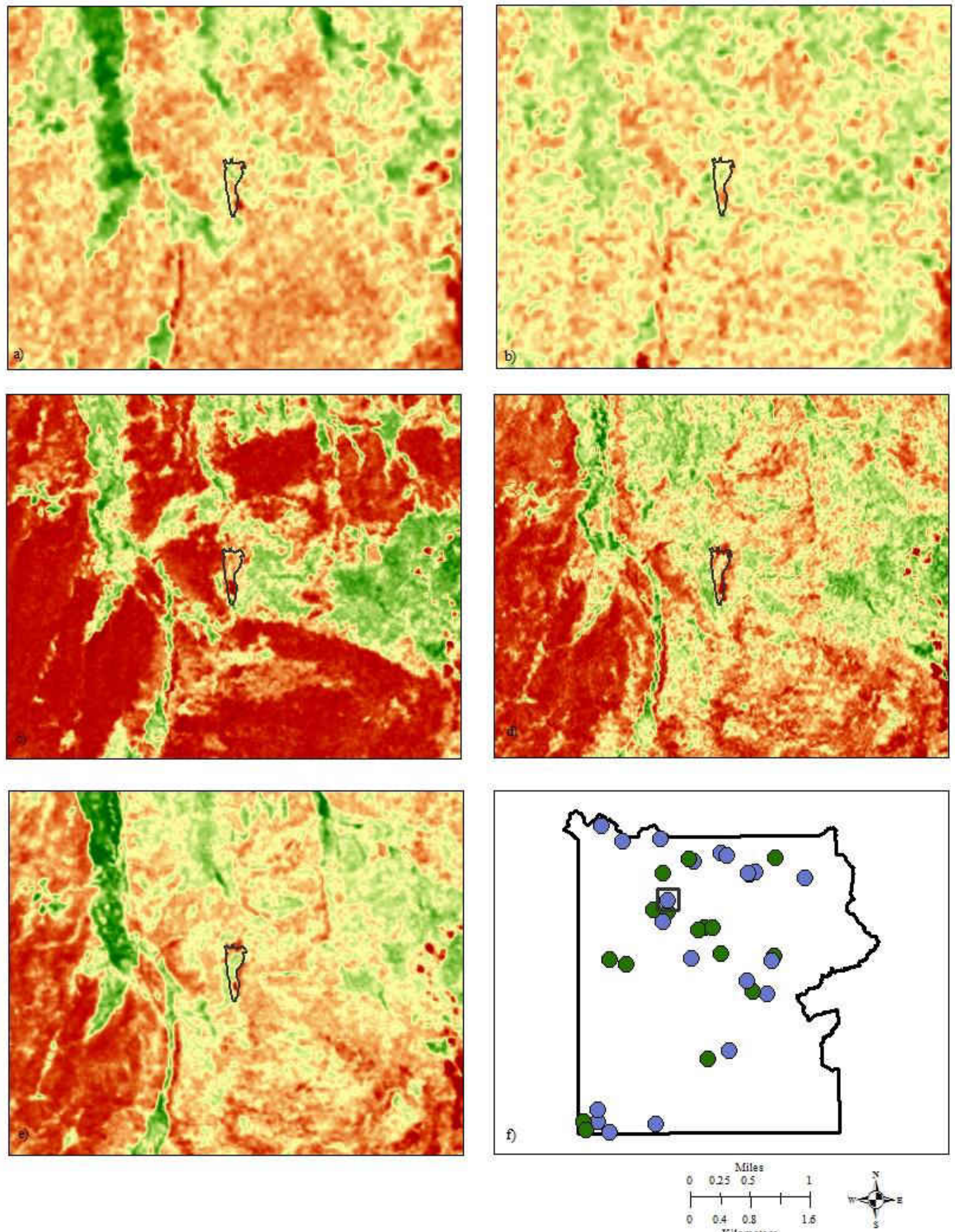

Figure 63. NDVI image of the Obsidian Lake historical nesting site.

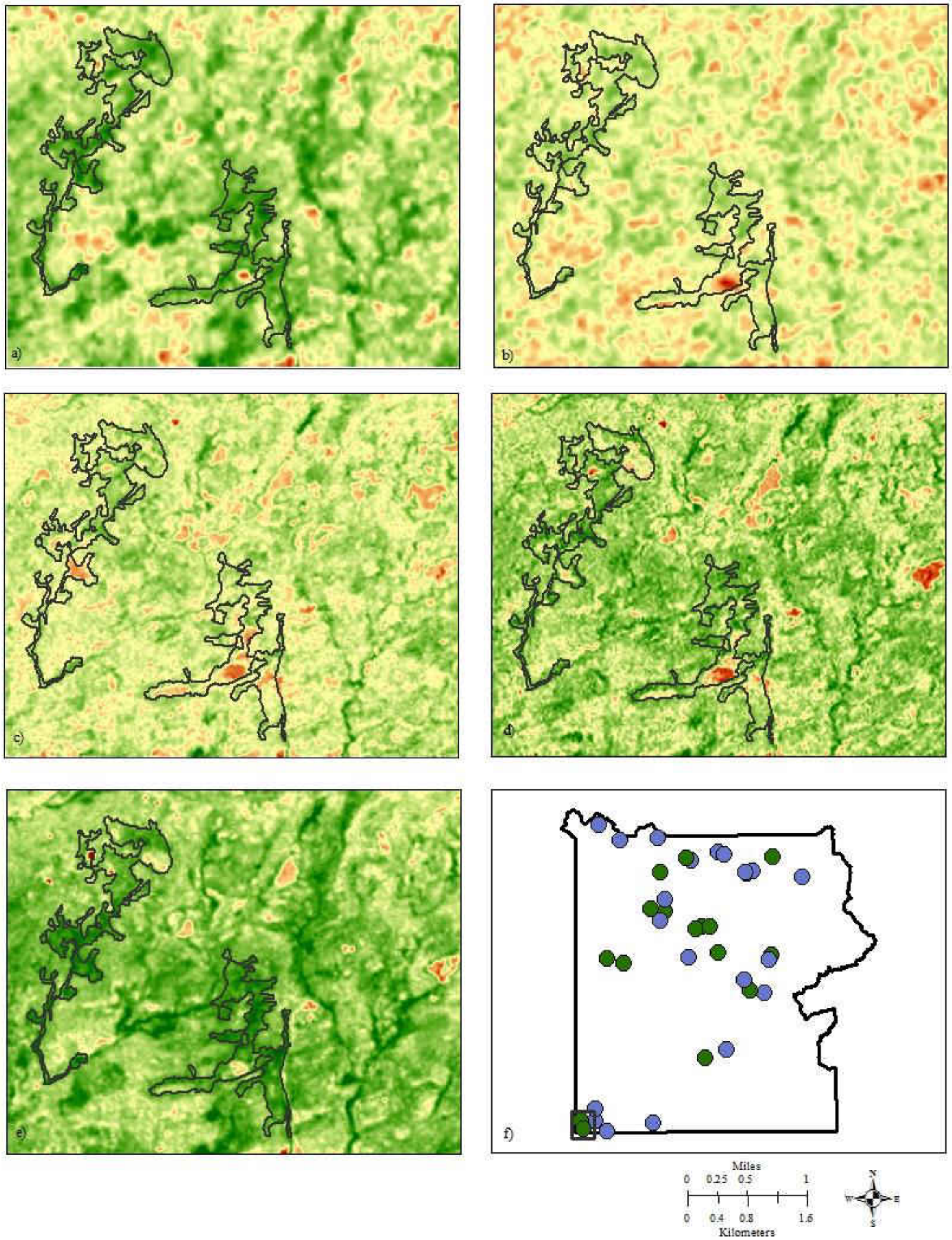

Figure 64. NDVI image of the Phoneline Lake and Robinson Lake historical nesting sites.

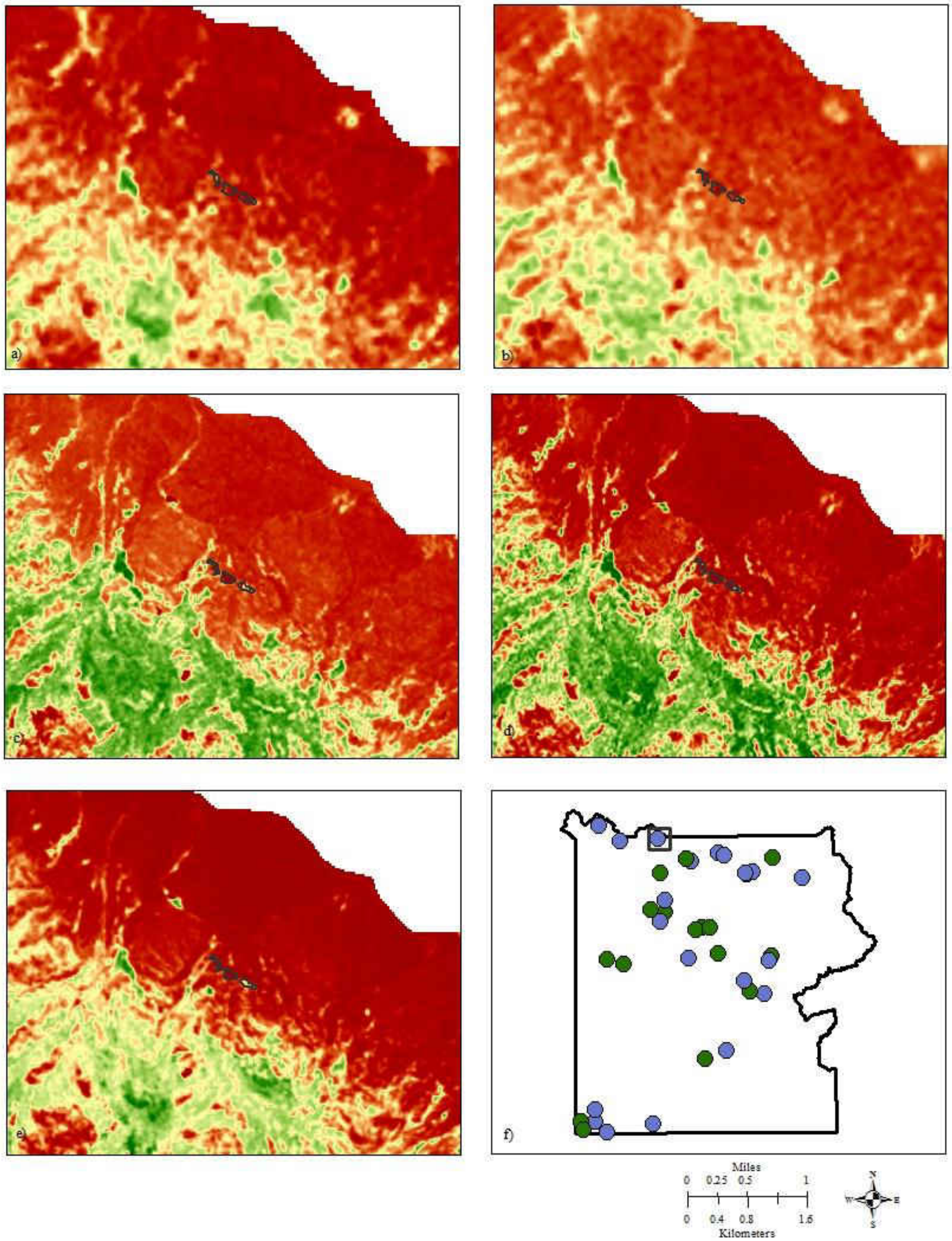

Figure 65. NDVI image of the Rainbow Lakes historical nesting site.

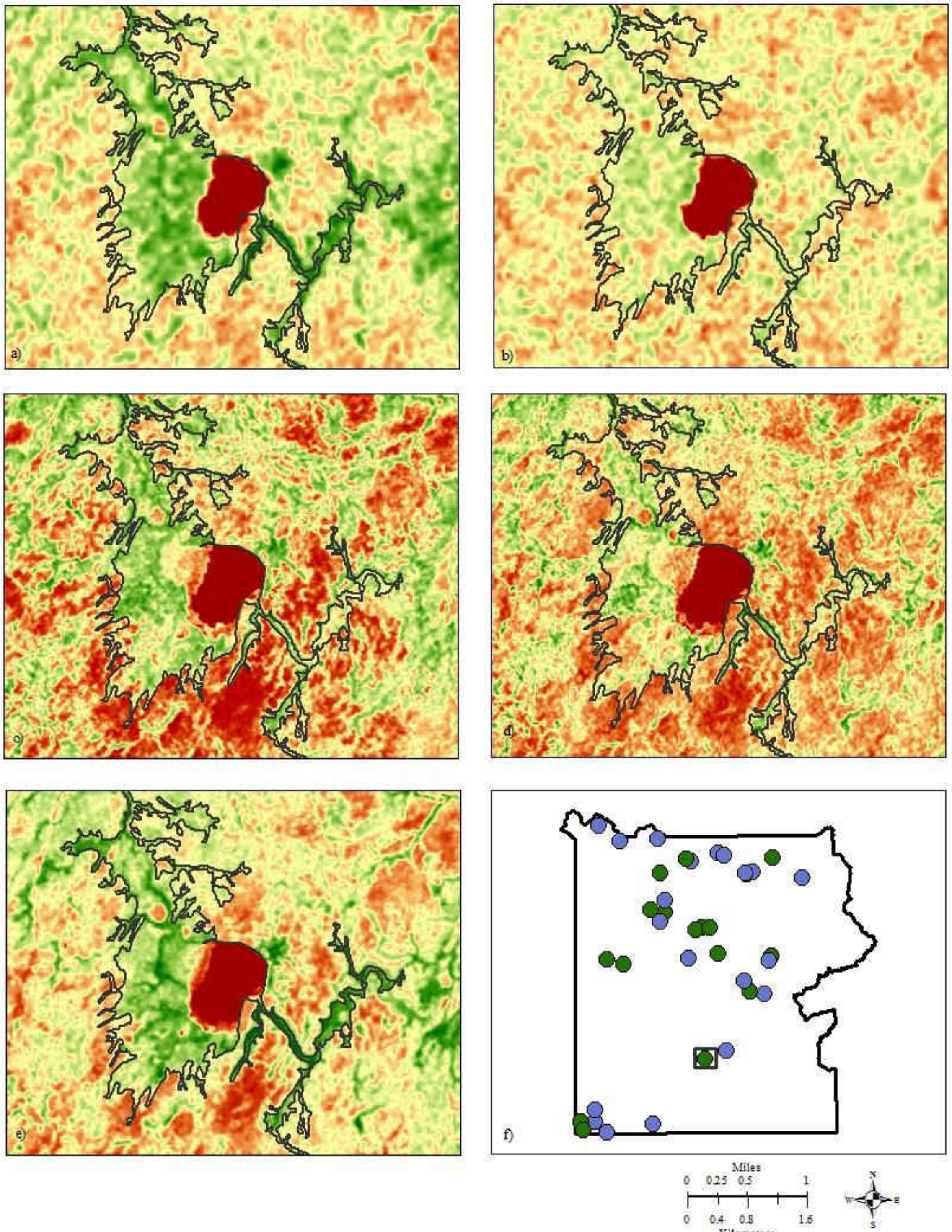

Figure 66. NDVI image of the Riddle Lake historical nesting site.

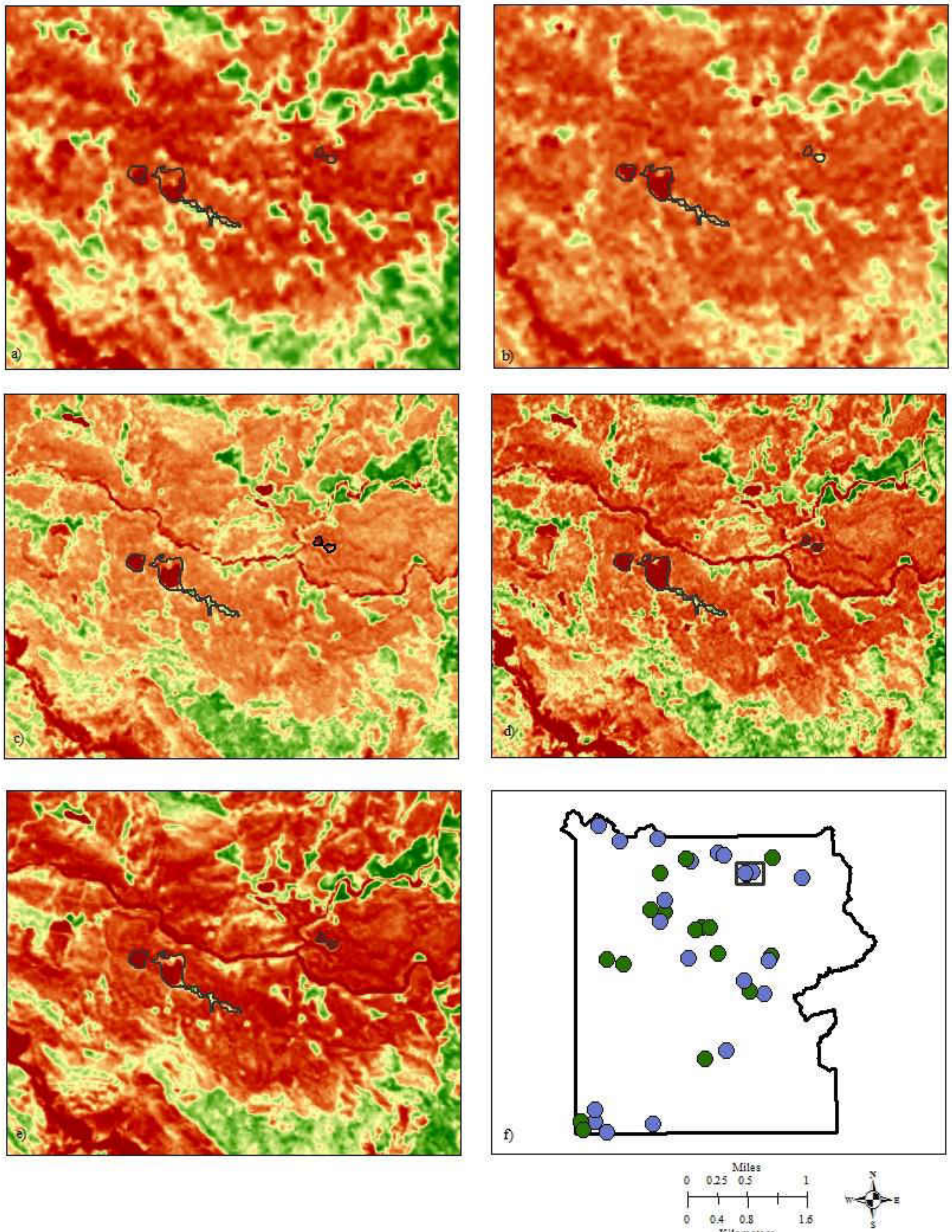

Figure 67. NDVI image of the Slough Creek Ponds and Trumpeter Lakes historical nesting sites.

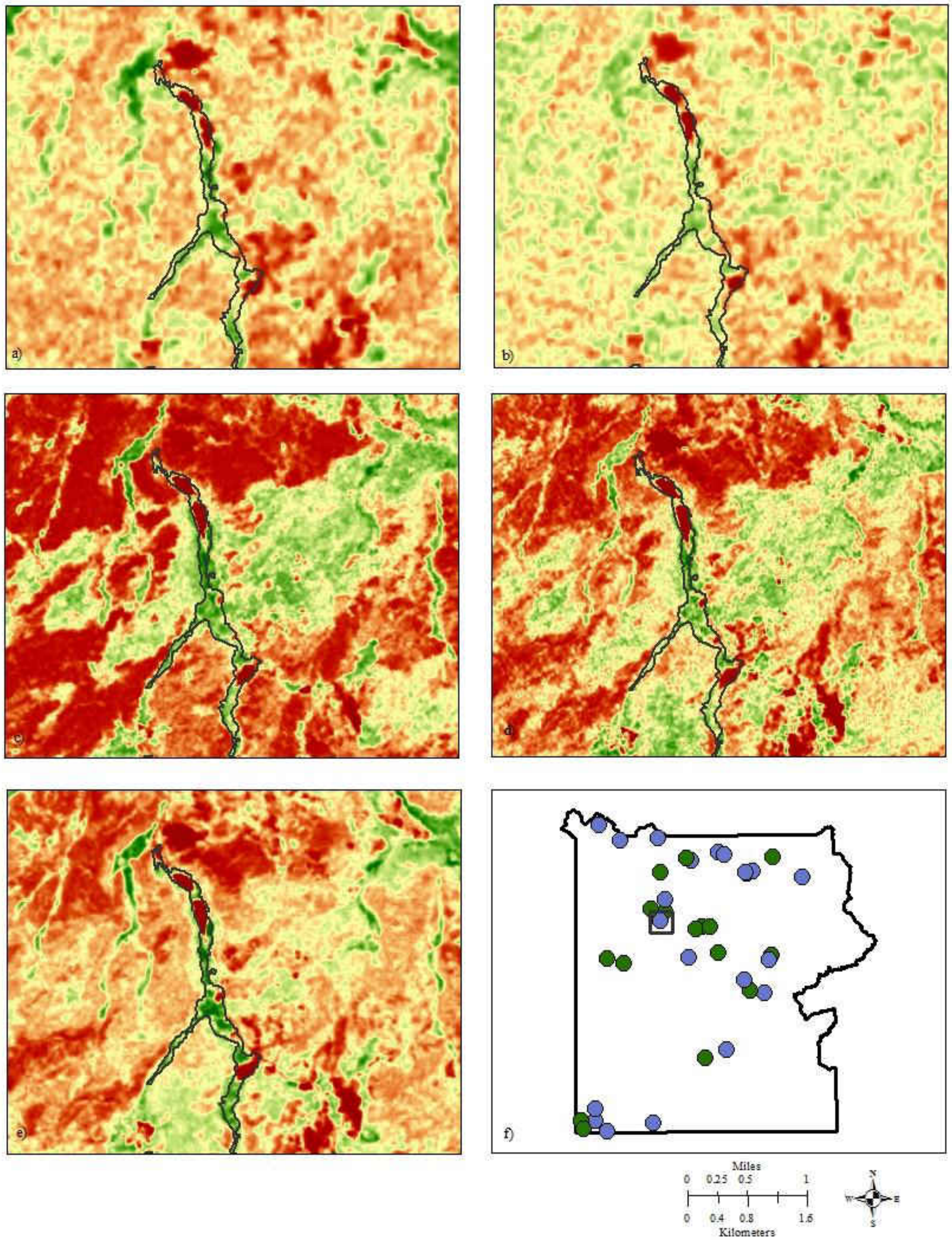

Figure 68. NDVI image of the South Twin Lake historical nesting site.

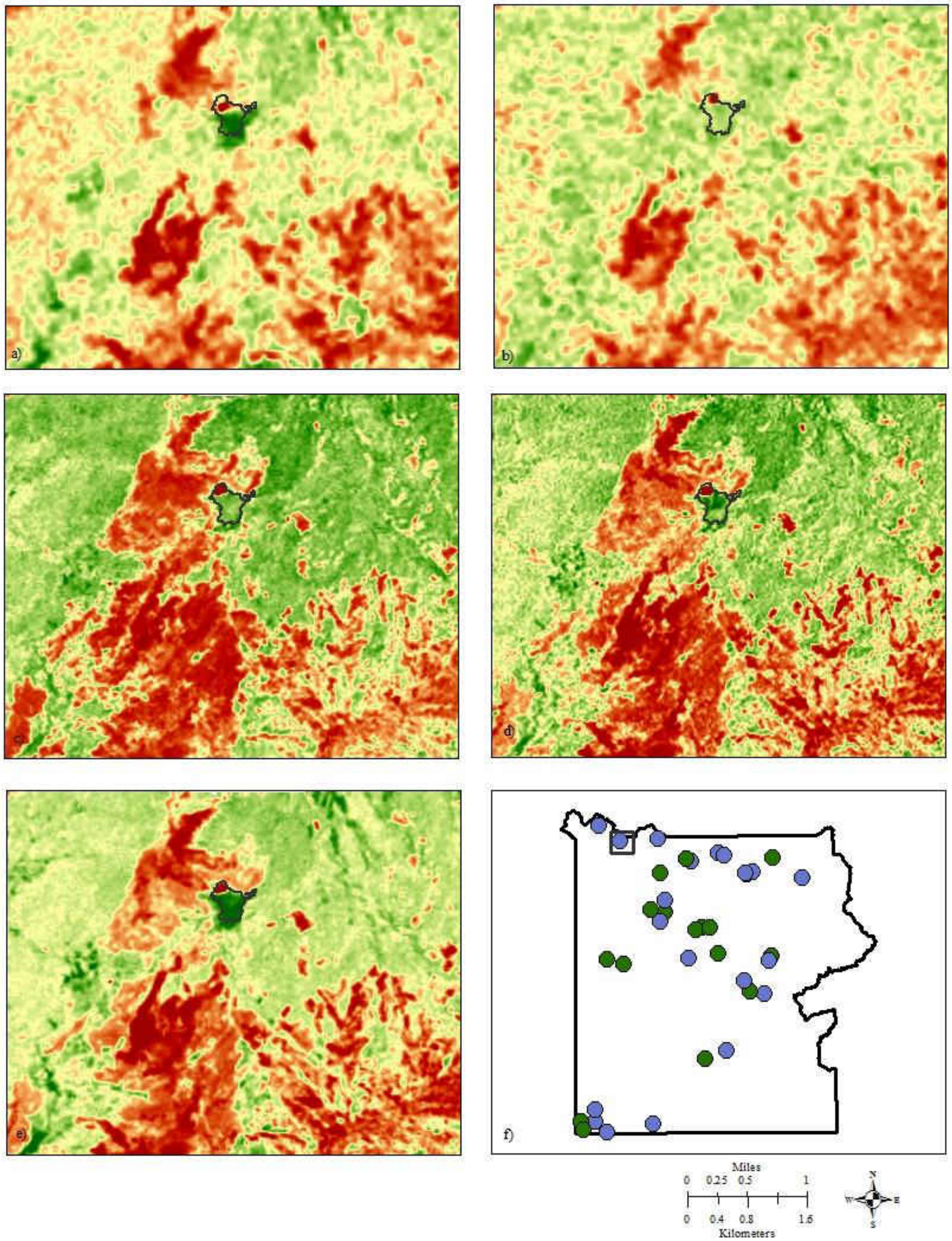

Figure 69. NDVI image of the Sportsman Lake historical nesting site.

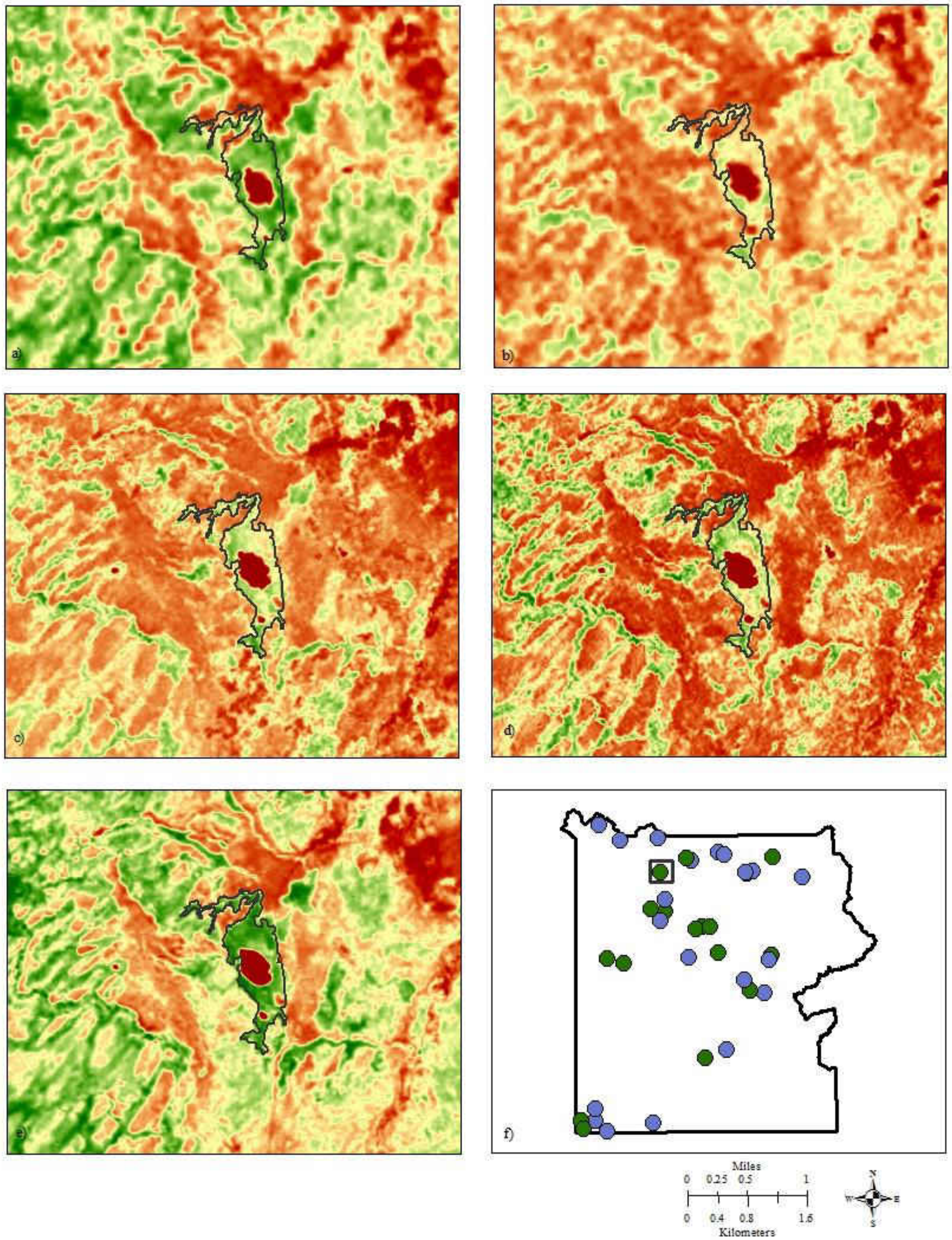

Figure 70. NDVI image of the Swan Lake historical nesting site.

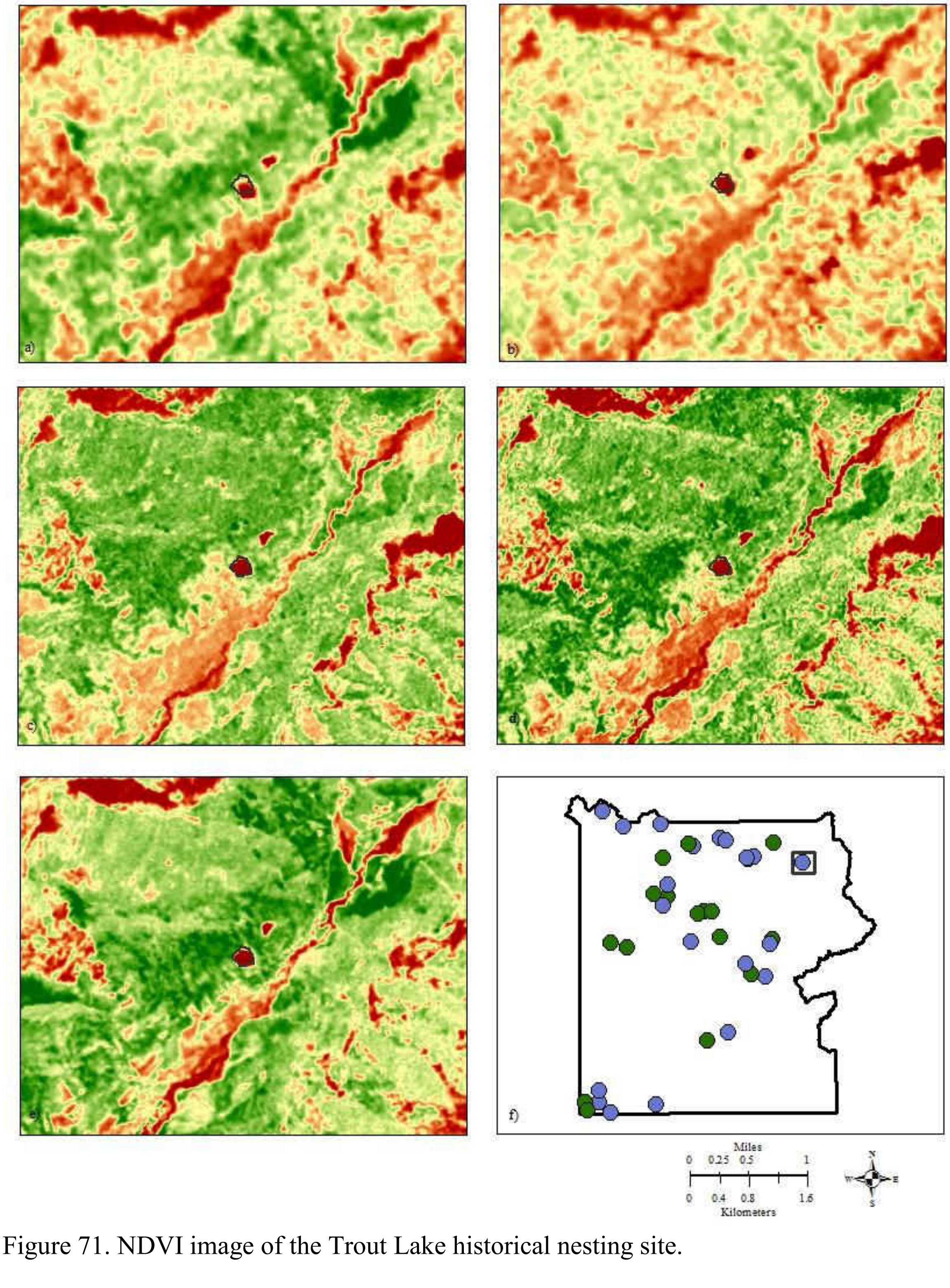

Figure 71. NDVI image of the Trout Lake historical nesting site.

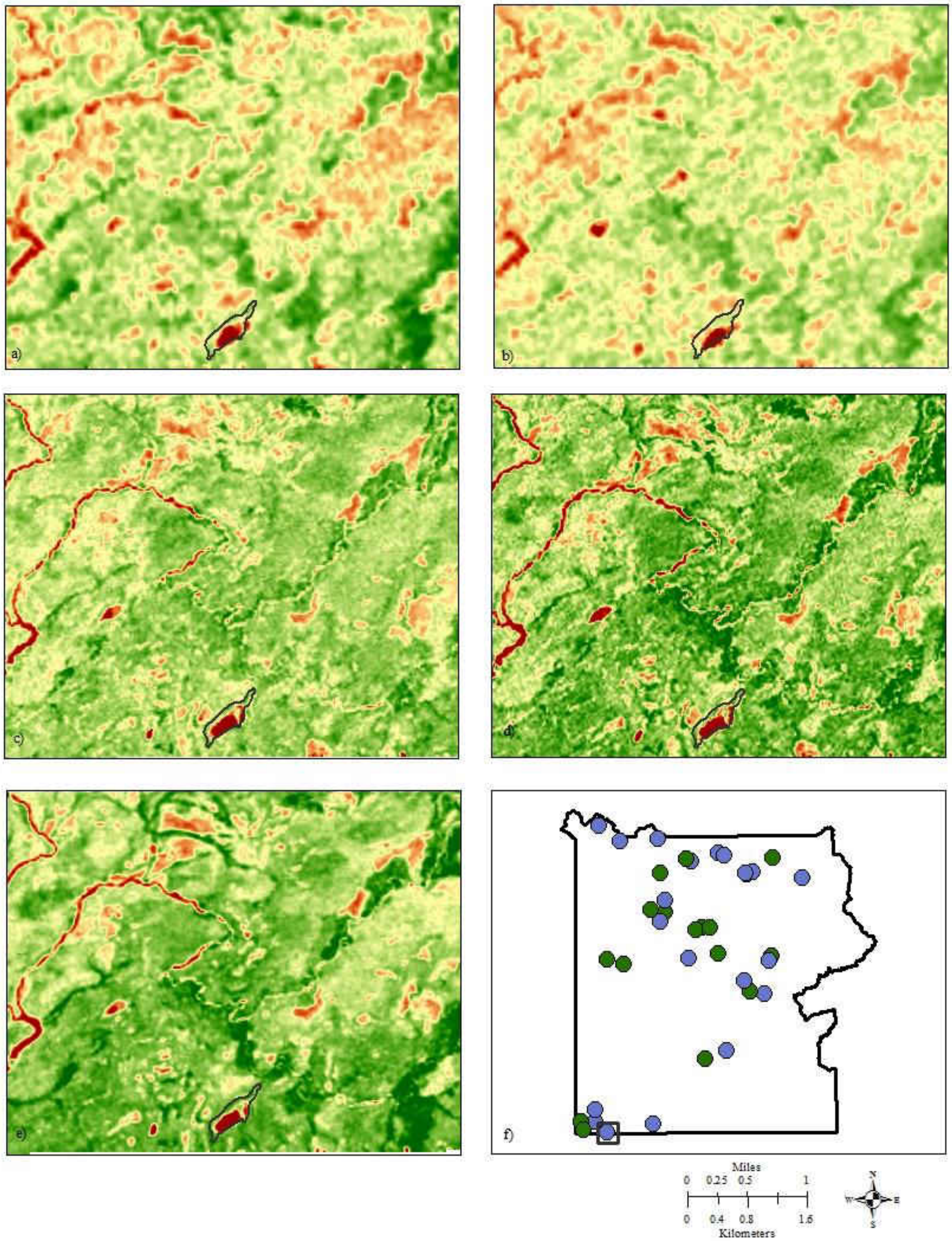

Figure 72. NDVI image of the Winegar Lake historical nesting site.

APPENDIX E:
VIEWER-SUBJECTIVE EVALUATIONS

Sampled wetlands were evaluated through visual inspection. Both false-color composite images which were created using all available Landsat bands and NDVI calculated images were evaluated for changes to the wetland area and surrounding landscapes to distinguish changes over time which may provide insight into trumpeter swan nesting efforts.

Alum Creek

The Alum Creek location was in an open meadow at the confluence of Alum Creek and the Yellowstone River along the Grand Loop Highway. The area of Alum Creek directly adjacent to the highway and confluence of the Yellowstone River was heavily braided and primarily barren of vegetation with mudflats and sparse sedges. This mudflat region was distinguished in all years of viewer observations, and with observable increases of the mudflat each year in both the composite and NDVI images, distinguished by a decrease in vegetation at the confluence. The most prominent landscape feature noted was Sulphur Spring to the south-east, and the Yellowstone River. Lodgepole Pine mixed forest areas were located to the north-west of the Alum Creek site, with a large patch of forest adjacent to the site. This area appeared densely forested in the 1975 and 1979 MSS images, while the 1990 TM image shows distinct changes; due to the 1988 forest fires, a portion of the forested area was involved in canopy and mixed burn. The Grand Loop Highway was barely distinguished in the MSS images, but noted in the 1990, 1999, and 2005 composite and NDVI images. The Mary Mountain trailhead was within the scope of the image but not visually located.

Beach Springs Lagoon and Pelican Creek

Beach Springs Lagoon and Pelican Creek were located in close proximity to one another and therefore were the images were grouped as landscape-level features were comparable due to location. The Pelican Creek location was at the mouth of Pelican Creek where it flowed into Yellowstone Lake. This area was open due to the wet soils associated with the creek meandering through the valley between the Lodgepole Pine mixed forest. The open water at the mouth of Pelican Creek was not noticeable in images other than the 2005 ETM+ image. Plant vigor in the

Pelican Creek area was highest in 1975 and 2005 according to the NDVI image. Beach Springs Lagoon was a small, spring fed wetland in open sagebrush along Mary's Bay. Beach Springs Lagoon showed an increase in vegetation in 1979, while other images showed large areas of open water. Sulphur Hills was distinguished easily in the top middle of the composite images, as was Steamboat Springs in the bottom corner, and Indian Pond between Pelican Creek and Beach Springs Lagoon. The East Entrance road bisected the Pelican Creek site, but was indistinguishable in both MSS images, and barely visible in the 1999 ETM+ image. In the 1990, 1999, and 2005 images, where the roadway was distinguished it was difficult to separate from the beach at Mary's Bay. The Fishing Bridge RV Park, including the water treatment facility, was distinguished in all images and it was noted that the RV Park was within the 1.0 km buffer that was used to characterize areas with potential human disturbance. Other man-made features located on the landscape were the Pelican Valley trailhead and a picnic area on Mary's Bay; neither were located on the Landsat images.

Bechler Meadows and Lilypad Lake

Bechler Meadows and Lilypad Lake images were located in close proximity to one another and therefore were grouped as landscape-level features were comparable due to location. Bechler Meadows was an incredibly complex braided wetland system comprised of the Bechler River, and tributaries including Boundary Creek and Bartlett Slough, with several non-forested wetlands identified over the meadow region such as willow and sedge bogs. The fluvial valley indicated the highest plant vigor in the 1975 NDVI image. The Bechler River was easily distinguished in the composite image from 1979 to 1999, with some indication of oxbows present in the 1990 image. Lilypad Lake was located on the south end of Bechler Meadows and surrounded by Lodgepole Pine mixed forest. Composite images and NDVI analysis indicated the majority of the open water during the analysis period was located in the middle of the lake. Ranger Lake and Falls River were easily distinguished in most NDVI images, but were difficult to distinguish in the MSS composite images, likely due to the larger resolution. The south-west region of the park had little development, and no man-made level disturbances were found.

Beula Lake

Beula Lake was a large lake surrounded by Subalpine Fir forest near the southern boundary of YNP and connected via stream and forested wetlands to Herring Lake. The forest fires of 1988 showed damage on the landscape level to the Subalpine Fir forest area as observed in the 1990, 1999, and 2005 composite and NDVI images. An area of small hot springs which feed a tributary of the Falls River were visible in 2005 and barely discernable in 1999; no other images were clear enough to distinguish the hot springs. South Boundary Lake was visible in all images to the south of the Beula Lake and Herring Lake region. The meadow between Beula Lake and Herring Lake, and the wetland on the north-eastern edge of Beula Lake both showed good vegetation health measured by NDVI in all years except 1979. This trend also followed in the wetlands surrounding the Falls River, but a dramatic loss of vegetation was measured in 1990 NDVI images south of the Falls River. This region of the park had little development; two backcountry campsites were located at Beula Lake and no man-made level disturbances were found.

Blacktail Ponds and Mount Everts Lake

Blacktail Ponds and Mount Everts Lake were located in close proximity to one another and therefore the images were grouped as landscape-level features were comparable due to location. Blacktail Ponds was a series of small lakes and wetlands near Blacktail Deer Creek at the base of the Blacktail Plateau. Mount Everts was a small lake located on a hilltop above the Blacktail Ponds. The steep hillside which separated the two, and other similar areas, was distinct due to the lack of vegetation on the downslope. Both areas were subject to varying levels of non-forested burn during the 1988 wildfires with some areas of forested burn visible on the landscape. The fire scars in the image were more prominent in the Douglas-fir forested areas than in the non-forested scrub-sagebrush area surrounding Blacktail Ponds and Mount Everts Lake. A section of the Grand Loop Road was directly visible from the Blacktail Ponds and within view on the landscape images and was visible in ETM+ images and the TM image, but not on the MSS images. The Blacktail Creek Trailhead parking lot was located adjacent to the wetlands but was not distinguishable in any of the images.

Cascade Lake, Grebe Lake, and Wolf Lake

Cascade Lake, Grebe Lake, and Wolf Lake were located in close proximity to one another and therefore the images were grouped as landscape-level features were comparable due to location. The lakes formed a series of large lakes along the top edge of the Solfatara Plateau, with the headwaters of the Gibbon River flowing to the west. To the south and north-west was Lodgepole Pine mixed forest, with Whitebark Pine mixed forest to the north-east. The forest fires of 1988 had a definite impact on forests to the south of the lakes, with the difference in forested area visible to the south severely impacted in the 1990 image with scars visible in the 1999 and 2005 images. Each lake had backcountry campsites located around the shore, but these features could not be located on the Landsat images. The Norris-Canyon Road and Grand Loop Road, Canyon Village, the Cascade Lake picnic area and trailhead, and the Cascade Creek trailhead were all located within the scope of the image; the roads and visitor center area were all visible to some extent in all images examined. An equipment facility and service roads were located near the Canyon Village junction and visible in each image; this area grew noticeably between 1999 and 2005. The Cascade Lake trailhead and picnic area was clearly visible in 2005; the Cascade Creek trailhead was barely distinguished in the 2005 image. Neither trailhead was located in any other image.

Crescent Lake

Crescent Lake was a high mountain lake located on the north side of a steep talus slope in the Gallatin Range. Surrounding the lake was primarily Whitebark Pine mixed forest and talus slopes. Several small lakes were within the visible scope of the image and were easily identified, but lakes were over-identified in the image as some areas around Crescent Lake which looked similar to open water were instead shadows created by the northern aspect of the mountainous ridgeline. The images of Crescent Lake and other lakes in the region appeared to be deep water environments with little wetlands associated around the lakes. In the 1999 image, Crescent Lake had a color change from the typical color of open water to a color which was generally associated more with thermal features. The other lakes in the area were not affected by a similar change in color. A small area of Lodgepole Pine mixed forest located on the south slope of the Gallatin Range was subject to canopy and mixed forest burn in the 1988 forest fires. This region of the park had little development and the only man-made features near the lake were a backcountry campsite at the lake, the Crescent–High Lake Trail and Specimen Creek Trail; none of these features were visible in any of the Landsat images.

Cygnet Lakes

Cygnet Lakes was a series of small wetlands on the Central Plateau which were connected by Magpie Creek. The Cygnet Lakes were primarily in an open sedge bog meadow with Lodgepole Pine mixed forest surrounding the lakes. Several thermal features were visible along the eastern edge of the image; the Violet Springs and Mud Pot were easily distinguished in all images. The forest fires in 1988 had a significant impact on the landscape to the east of the Cygnet Lakes area. The mixed forest was subject to both canopy and mixed burn, while the open meadow was subject to non-forested burn. The burn scars were visible in images from 1990 to 2005 while the 1975 and 1979 images showed no fire scars. NDVI images indicated good vegetation health in 1975, while the 1990 image showed areas of minimal vegetation growth in the wetlands around the lake and the burned area. This region of the park had little development and the only man-made feature in the image was the Cygnet Lakes Trail which terminated at the southernmost tip of the opening into the meadows around the lakes; this feature was not visible in any of the images viewed.

East Tern Lake and White Lake

East Tern Lake and White Lake were located in close proximity to one another and the images were grouped as landscape-level features were comparable due to location. Along with White Lake and East Tern Lake being detected, West Tern Lake and Fern Lake were easily identified in all images. The lakes were surrounded by Lodgepole Pine mixed forest. The Ponunta Springs and other hot springs were distinguished in all composite images. The wildfires of 1988 burned around the Fern Lake area, and scars from the damage were visible in the 1990, 1999, and 2005 images. The NDVI images in these years also indicated that large areas with no vegetation were present in the burned region. The NDVI images of the wetland indicated that White Lake contained little vegetation, while East Tern Lake had a higher occurrence of vegetation within wetlands. This region of the park had little development with the only development the Astringent Creek Trail and a backcountry campsite north of Fern Lake. No man-made level disturbances were located in the images.

Geode Lake and Hellroaring Complex

Geode Lake and the Hellroaring Complex were located in close proximity to one another and the images were grouped as landscape-level features were comparable due to location. Geode Lake was a small lake located in a Douglas-fir forested, talus slope region near the Yellowstone River. The Hellroaring Complex was a small wetland located in open sagebrush habitat along the south side of Hellroaring Creek east of the confluence with the Yellowstone River. The Yellowstone River and Hellroaring Creek were easily visible, including some sections of rapids along the Yellowstone River. Steep hillsides were distinguished due to the barren area caused by landslides. The NDVI images showed the Yellowstone River as an area lacking vegetation while Hellroaring Creek showed up as an area with vegetation present. The NDVI images indicated that Geode Lake had little vegetation and the Hellroaring Complex NDVI image indicated little vegetation in the shallow area and increased vegetation in the lower region. A section of the Grand Loop Road was within view on the landscape and was visible in ETM+ images and the TM image, but not on the MSS images.

Grizzly Lake

This area was largely comprised of Lodgepole Pine mixed forest with some thermal features present, such as Roaring Mountain. Other thermal features distinguished included the Amphitheater Springs and the springs which fed Lemonade Creek. The area around Grizzly Lake was subject to a tremendous amount of canopy burn during the fires in 1988. In the inspection of images in 1975 and 1979, the areas were entirely forested prior to the forest fires. The NDVI image indicated that the vegetation health in the wetlands on the south side of Grizzly Lake were less vigorous than prior to the burn. A section of the Grand Loop Road was visible in the image, along with the Grizzly Lake trailhead; which was most visible as it paralleled Obsidian Creek.

Harlequin Lake and Seven Mile Bridge

Harlequin Lake and Seven Mile Bridge were located in close proximity to one another and the images were grouped as landscape-level features were comparable due to location. The wetlands that formed Seven Mile Bridge were heavily braided from the Madison River flooding through the Madison Canyon with water flowing through alternate channels and creating islands throughout the wetland. Harlequin Lake was a small lake located on a ridge above the valley floor. The area was consisted of Douglas-fir forest to the north of the Madison River, Lodgepole Pine mixed forest south, and open meadows with sedge bogs along the Madison River. The Madison Range, including Mount Jackson, were located in the image because of the lack of vegetation on the steep southern slopes. The area was subject to a patchy mosaic of forest fires in 1988, with heavy canopy to the south of the Madison River, areas of non-forested burn around the wetlands by Seven Mile Bridge, and patches of canopy and undifferentiated burn directly around Harlequin Lake. The area appeared to be heavily forested prior to the wildfires. NDVI images indicated healthy vegetation growth in the Seven Mile Bridge wetlands after the 1988 forest fires, while Harlequin Lake showed varying amounts of open water and vegetation growth around the lake without any pattern. A section of the West Entrance Road bordered the Madison River and was visible in all images; the Seven Mile Bridge trailhead could not be differentiated from the road, nor was Madison Junction or the Madison Campground.

Hidden Lakes

Hidden Lakes was two small wetlands located between Delusion Lake and the Flat Mountain Arm of Yellowstone Lake. Both Delusion Lake and Flat Mountain Arm were both visible in all images. This area was primarily comprised of Subalpine Fir and wet forest with open areas created by sedge bogs near the wetlands around Hidden Lakes. Only a small portion of open water existed on the wetlands, and the site was difficult to distinguish in both MSS images. The NDVI image showed good vegetation health in the wetland region in 1999 and 2005. This area was subject to forest fires in 1988 in the forested area between Delusion Lake and Hidden Lakes and immediately south of Hidden Lakes, although little fire damage was noted near Flat Mountain Arm. The change in vegetation was distinct as the wetlands stood out against the recently burned areas in the 1990 image, and the changes were more pronounced the 1999 and 2005 images. The NDVI image depicted the burned area as low NDVI, which indicated low plant growth or barren areas. This region of the park had little development with no trails or backcountry campsites, and no man-made level disturbances were located.

LeHardy Rapids to the Fishing Bridge

The LeHardy Rapids to Fishing Bridge nesting site was located along the Yellowstone River in a series of back sloughs along a valley surrounded by Lodgepole Pine mixed forest. The site was bordered on the west by the Grand Loop Road and on the east by the Howard Eaton Trail. LeHardy Rapids, Ochre Springs, and the hot springs associated with the Mud Volcano system were visible in the composite images; no vegetation changes were noted from the thermal features in the NDVI images. The NDVI image indicated vegetation vigor was highest in 1975 and in 2005. The Yellowstone River appeared in composite images to have large areas of sandbars in 1979 and 1990, which may be related to the low vegetation health measure in the NDVI images in those years. The Grand Loop Road was visible in all composite images, although the areas where the road bordered the Yellowstone River were difficult to distinguish between road and river. The road was most visible in the area where it intersected with the East Entrance Road just north of Lake Village and west of the Fishing Bridge RV Park. The Fishing Bridge RV Park and the Lake Village Visitor Center were both features that were distinguished in all composite images, although these features were not discerned in the NDVI images. A fire break underneath a transmission line was visible in the images from 1990, 1999, and 2005, but was not observed in the MSS images.

Lake of the Woods

This area was largely comprised of Lodgepole Pine mixed forest with some thermal features present, such as Roaring Mountain. Other thermal features distinguished included the Amphitheater Springs and the springs which fed Lemonade Creek. The area immediately around Lake of the Woods was burned during the forest fires in 1988, but large stretches around Lemonade Creek were unburned. In the inspection of images in 1975 and 1979, the areas were entirely forested prior to the forest fires. A section of the Grand Loop Road was visible in the image, along with the Solfatara North trailhead, and a clear cut under the transmission line that runs along the Solfatara Creek Trail. The transmission line was clearly visible in each image, while the road was most visible when it paralleled Obsidian Creek.

McBride Lake

McBride Lake was a small, narrow lake located on the top of a rock outcropping above Slough Creek at the base of Buffalo Plateau with a series of wetlands created by oxbows from the movement of Slough Creek throughout the valley below. Sandbars were distinguished along the lower stretch of Slough Creek in the composite images. McBride Lake were an open water with little aquatic vegetation indicated through NDVI images. The forest fires of 1988 had a small impact in the Slough Creek area, with some non-forested and undifferentiated burns around McBride Lake and to the west at the base of the Buffalo Plateau. Minimal scarring was observed in the later composite images, and these changes to the landscape were not reflected in NDVI images. This region of the park had little development with a few backcountry campsites and a patrol cabin in the valley; no man-made level disturbances were located.

Obsidian Lake

Obsidian Lake was a small, narrow lake located at the top of the Obsidian Canyon with a small wetland locate near the steep western slope into the canyon. The lake was surrounded by Lodgepole Pine mixed forest. Obsidian Lake was difficult to distinguish in the MSS images as the area of open water was too small for the resolution to detect any changes within the lake basin. The area to the west and south of Obsidian Lake was subject to almost continuous burns from the 1988 forest fires, with the exception being near wetlands created from Obsidian Creek opening out of the canyon and outflow from Apollinaris Spring. The NDVI images reflected the vegetation changes due to the forest fire, and the Obsidian Lake wetlands showed increased plant health only in 1999. A section of the Grand Loop Road traveled through the Obsidian Canyon below Obsidian Lake and was visible in all images; the Mount Holmes trailhead could not be differentiated in any images. A transmission line was visible due to the clear cut area underneath the lines through the forested area but not through the open meadow in all composite images.

Phoneline Lake and Robinson Lake

Phoneline Lake and Robinson Lake were located in close proximity to one another and the images were grouped as landscape-level features were comparable due to location. Both lakes were surrounded by Lodgepole Pine mixed forest, with the sedge bog wetlands providing open areas from trees. These clearings were detected in both composite and NDVI images. Neither lake had indication of large areas of open water in the wetland environment; both areas when sampled were primarily emergent vegetation. Robinson Creek was a prominent feature due to the gully formation where the creek meandered. The south-west region of the park had little development; the Bechler Ranger Station and the gravel road to the station were the only man-made features. The Ranger Station was barely detected in any image and the roadway was undetected.

Rainbow Lakes

Rainbow Lakes were a series of small lakes located near the northern boundary of YNP and fed by Landslide Creek. This northern slope in this area was an arid, open sagebrush habitat, while the southern slope was dominated by Douglas-fir forest. The NDVI images indicated that the southern slope with the forest was high in vegetative growth while the northern slope was primarily devoid of vegetation. This was likely related to a rain shadow effect caused by the northern slope in this region. The wetlands around Rainbow Lakes were always visible in the composite image, likely because they were a source of water which was a dynamic feature on the dry landscape. This site was located near the border of YNP and the town of Gardiner MT was not visible as all area outside YNP had been removed from analysis. The Stevens Creek Road and Stephen's Creek Bison Capture Facility were located within the scope of the image; sections of the road were distinguished in all images while the Bison Facility was most easily defined in the 2005 image and not clearly distinguished in any other image.

Riddle Lake

Riddle Lake was a large lake in a Subalpine Fir area surrounded by extensive wetlands which open the landscape by excluding the forest. Open areas created by wetlands were visible on composite images due to the lack of forest on the landscape, but these features were not distinguished in the NDVI images. The wildfires of 1988 created several areas of deforested land around Riddle Lake which were evident in the 1990, 1999, and 2005 composite images, but not pronounced in the NDVI images. The wetlands around Riddle Lake prevented extensive damage through the region, but some areas still experienced heavy mixed and canopy burns. The Grant Village Visitor Center was located at the south end of the West Thumb of Yellowstone Lake and was visible all composite images, as was the South Entrance Road.

Slough Creek Ponds and Trumpeter Lakes

Slough Creek Ponds and Trumpeter Lakes were located in close proximity to one another and the images were grouped as landscape-level features were comparable due to location. Both locations were located in open sagebrush habitat with the Lamar River and Slough Creek joining just west of Slough Creek Ponds forming sedge bogs. Trumpeter Lakes was visible in all images, with varying levels of open water and mudflats. Slough Creek Ponds was often difficult to distinguish, likely due to the resolution of the MSS images. The Lamar River and Slough Creek, as well as the wetlands created by the confluence of Slough Creek into the Lamar River were all easily distinguished. The Northeast Entrance Road traversed east to west just south of the two nesting locations; the roadway was largely undetectable in the composite images and was the only man-made feature on the landscape.

South Twin Lake

South Twin Lake was the southern lake in a connected pair of lakes surrounded by Lodgepole Pine mixed forest. The area which connected the two lakes was mostly forested, while the wetlands at the southern end of South Twin Lake were more extensive. To the south, Nymph Lake was identified as an open water habitat, with thermal features located on the northern side. Roaring Mountain was easily located in each image, while smaller thermal features like Roadside Springs and Bijah Springs were harder to distinguish in the MSS images. The area around South Twin Lake was not subject to burns in the 1988 forest fires, but extensive stretches of canopy burn extended to the west of the Twin Lakes, and around the North Twin Lake. The fire scars were widespread through inspection of the NDVI images following the fires, and the composite images showed obvious changes to the forest in the burned region. Sections of the Grand Loop Road traveled past the Twin Lakes and was visible in the 1990 and 1999 composite images; no other man-made features were located in the images.

Sportsman Lake

Sportsman Lake was a small lake at the base of a large ridge surrounded by Whitebark Pine forest to the south and Lodgepole Pine mixed forest to the north. To the north was a steep cliff which confined the open meadow created by the lake and Mullherin Creek to the south. The meadow area showed good vegetation in the 1979 and 2005 NDVI images. Small patches of mixed and canopy burn from the 1988 forest fires stretched through the area around Sportsman Lake. While the area of damage did not appear to be serious, the fire scars viewed in the TM and ETM+ images indicated that the damage was severe. This region of the park had little development and the only man-made features near the lake were backcountry campsites at the lake, a patrol cabin, and the Sportsman Lake Trail; none of these features were visible in any of the images.

Swan Lake

Swan Lake was a large lake located on Swan Lake Flats which was an open, sagebrush on the eastern base of the Gallatin Range. Lodgepole Pine mixed forests existed on the far southeast side of the Flats region. Vegetation health in the wetlands around Swan Lake indicated the highest vegetation health in 1975 and 2005. Panther Creek, Indian Creek, and Obsidian Creek all join the Gardner River on the south end of the Flat, after they join the Gardner River flows into a canyon Sheepeater Cliffs. The creek beds and wetlands around the creeks were visible in all images, as were the Cliffs. Bunsen Peak was visible as the southern slope had little vegetation due to the steep slope. The entire Flats area was subject to grassland burns, with canopy and mixed forest fire burns to the east in the 1988 forest fires. The forest damage appeared to be more extensive than the grasslands fire damage in the composite images and NDVI images. The Grand Loop Road traversed north to south, running on the eastern edge of Swan Lake with a vehicle pull-out and view point of the Gallatin Range directly along the eastern shore of Swan Lake; both these features were visible in the TM and ETM+ images. A transmission line ran through the area but was not visible as it ran through the open meadow in all composite images and no clear cut was present in conjunction with the line.

Trout Lake

Trout Lake was a small lake located near the Northeast Entrance Road, located in the open sagebrush-fescue habitat, on the edge of a larger Douglas-fir forest region. Trout Lake appeared to have a well-defined shoreline with little aquatic vegetation throughout the analyzed images. Another small lake, Buck Lake, was easily distinguished, as was Soda Butte Creek along the base of Soda Butte Canyon. Several areas to the east of Trout Lake initially appeared to be open water, but on further inspection these areas were from the shadow on the northern aspect of The Thunderer. Several areas to the north-west of Trout Lake were similar in appearance to many of the hot springs that had been located in other images; these features were identified upon further analysis as eroded cliff edges. The sandbars along Soda Butte Creek were easily identified, and contributed to the lack of vegetation measured by the NDVI images. The Pebble Creek Campground was located within the observable aspect of the images, but was not distinguished in the composite or NDVI images.

Winegar Lake

Winegar Lake was a small lake surrounded by Lodgepole Pine mixed forest located near the southern boundary of YNP. Several small wetlands were in close proximity to Winegar Lake; these were not always easily distinguished in MSS images, likely due to the resolution of older Landsat images. Falls River was the largest landscape feature in the scope of the image, and the section which flows through the Falls River Basin was difficult to distinguish in the 1975 and 1979 images, likely due to the braiding and oxbows which create no defined channel. Several falls and rapids along the Falls River were distinguished in all composite images. The NDVI image indicated that the majority of the open water was located in the south-west portion of the lake, with varying amounts of aquatic vegetation in the north-east portion of the lake. The south-west region of YNP had little development, and no man-made level disturbances were found.