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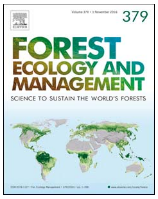

Using MODIS NDVI phenoclasses and phenoclusters to characterize wildlife habitat: Mexican spotted owl as a case study

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ABSTRACT

Most uses of remotely sensed satellite data to characterize wildlife habitat have used metrics such as mean NDVI (Normalized Difference Vegetation Index) in a year or season. These simple metrics do not take advantage of the temporal patterns in NDVI within and across years and the spatial arrangement of cells with various temporal NDVI signatures. Here we use 13 years of data from MODIS (Moderate Resolution Imaging Spectroradiometer) to bin individual MODIS pixels (5.3 ha) into phenoclasses, where each phenoclass consists of pixels with a particular temporal profile of NDVI, regardless of spatial location. We present novel procedures that assign sites to phenoclusters, defined as particular composition of phenoclasses within a 1 km radius. We apply these procedures to Mexican spotted owl (*Strix occidentalis lucida*) nesting locations in the Sacramento Mountain range in south-central New Mexico. Phenoclasses at owl nest sites and phenoclusters around owl nest sites differed from those at and around points randomly placed in forest types that are known to support nesting owls. Stand exam data showed that the phenoclasses associated with owl nest sites are dominated by Douglas-fir (*Pseudotsuga menziesii*) and white fir (*Abies concolor*). The availability of phenoclusters and phenoclasses on Mescalero Apache tribal lands differed from those on adjacent National Forest lands within the Sacramento Mountain, consistent with different elevations and forest management practices. Nonetheless owls predominately used the same phenoclasses and phenoclusters in both land ownerships. MODIS phenoclasses and phenoclusters offer a useful means of remotely identifying forest conditions suitable for wildlife. Because the remote sensing data are freely available and regularly updated, they can be part of a cost effective approach to monitor and assess forested wildlife habitat over large temporal and spatial scales.

1. Introduction

Characterizing, managing, and monitoring habitat of wildlife in dynamic landscapes is one of the biggest challenges facing natural resource managers, especially for broadly distributed rare species (Morrison et al., 2012; Sharik et al., 2010; Bartel and Sexton, 2009). Data obtained by satellites are often used to help characterize habitat at large spatial scales including remote regions (Jones and Vaughan, 2010; Gottschalk et al., 2005). In the U.S., for example, national and regional GAP Land Cover is derived from models in which the predictor variables are provided by Landsat Thematic Mapper imagery (USGS, 2011). Another example is Normalized Difference Vegetation Index (NDVI), which estimates photosynthetic activity by measurements (typically from a satellite) of the relative amounts of electromagnetic radiation at 0.66 μm and 0.86 μm (NASA, 2016; Sellers, 1985; Sellers, 1987; Tucker and Sellers, 1986). Many studies have used NDVI estimated at a single point in time, or the average NDVI across a year or season, to help model or map potential habitat (e.g., Shirley et al., 2013; Gillespie et al., 2008; Goetz et al., 2007; McDermid et al., 2005; Venier et al., 2004; Franklin et al., 2002; Osborne et al., 2001; Thibault et al., 1998). A few studies used the intra-annual NDVI profile (a plot of NDVI across dates within a year) to map or predict species occurrence or habitat conditions (Osborne et al., 2001; Kremer and Running, 1993; Wallin et al., 1992). In each case, the temporal NDVI profiles differed between groups (e.g., sites where a species did or did not occur).

In this paper we introduce a new way to use temporal NDVI profiles in studies of wildlife habitat. Specifically, we use a set of temporal NDVI profiles developed for the conterminous U.S. as phenoclasses. Hoffman et al. (2013) produced these phenoclasses from unsupervised classifications of 5.3 ha MODIS pixels (MODIS NDVI Data) based on their annual NDVI profiles over 13 years (2000–2012) (Fig. 1), using methods adopted from White et al. (2005). Each phenological signature

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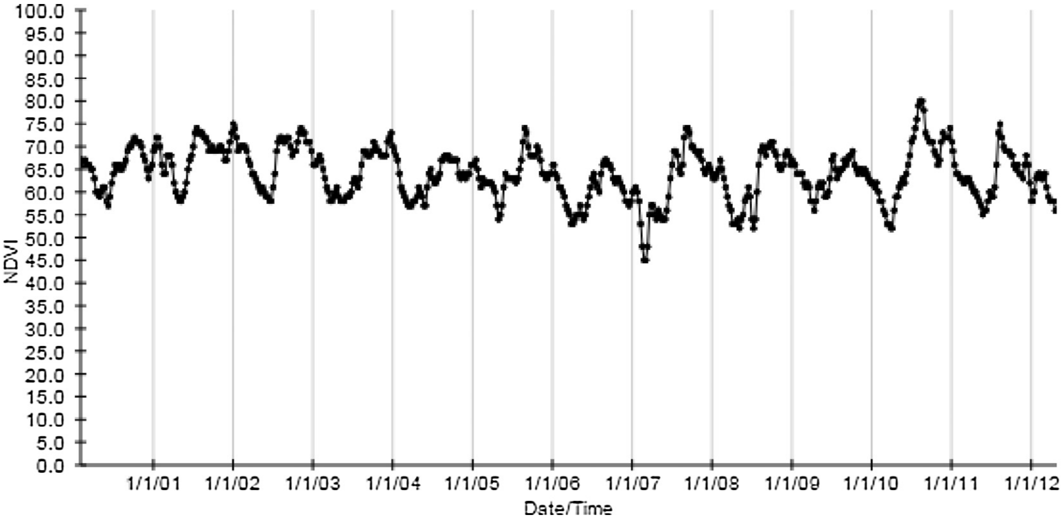


Fig. 1. Normalized Difference Vegetation Index (NDVI) values for an individual MODIS pixel within our study region (Lat: 33.2690 Lon: −105.6095) over the 13 year period (2000–2012). Note the cyclical/reoccurring patterns of higher NDVI values during the growing seasons and lower NDVI values during the winter. Click on the following link to see the map with approximate location of selected pixel: http://forwarn.forestthreats.org/fcav2?theme=CONUS_Vegetation_Monitoring_Tools&layers=PR100MM,AAB&mask=Forest&alphas=1,1&accgp=G04&basemap=Streets&extent=-11791140.499198,3909184.8810125,-11729990.87657,3947823.7988107.

proportionally reflects the seasonal photosynthetic activity of all vegetation types present within a pixel. Thus, each phenoclass can be conceptualized as a vegetation assemblage, or the structure and composition of a site relative to a continuum of vegetation conditions. Expanding beyond a single pixel, we further group neighborhoods (e.g., all pixels within 1 km of a site) into phenoclusters, such that the composition of phenoclasses of neighborhoods in each phenocluster are more similar to each other than to the composition of phenoclasses of neighborhoods assigned to other phenoclusters. Together, phenoclasses and phenoclusters characterize habitat at spatial scales from the individual 5.3 ha pixel up to the neighborhood size (302 ha). We believe this paper is the first application of phenoclass as an indicator of wildlife habitat, and the first use of phenocluster in any context.

In this paper, we describe the process for using NDVI phenoclasses and phenoclusters, as applied to forests used by the Mexican spotted owl in the Sacramento Mountains of New Mexico (Fig. 2). If phenoclasses and phenoclusters can distinguish owl sites from random sites on the landscape, then they can be used to create habitat suitability maps, and can become an innovative, rapid way to assess and monitor habitat of owls over large spatial and temporal scales. To further explore the utility of these descriptors, we used stand exams to characterize phenoclasses and to explain owl associations with certain phenoclasses and phenoclusters in light of previous work on habitat selection by the owl. We further explored whether availability of phenoclasses and owl use differed between the two major land ownerships in the Sacramento Mountains.

2. Methods

2.1. MODIS data

MODIS (Moderate Resolution Imaging Spectroradiometer) satellite images are obtained from the passive sensor systems aboard the Terra and Aqua sun-synchronous satellites. These satellites are designed to monitor the surface of the earth for 15 years and fly in polar orbits, which provide global coverage and repeat sampling under constant illumination. MODIS provides a favorable trade-off between image resolution (231 × 231 m or 5.3 ha) and temporal frequency of imaging. For example, MODIS images are obtained for most locations daily whereas the return time for Landsat is 16 days (Jones and Vaughan, 2010). The shorter return time provides more cloud-free compositing to generate 46 NDVI values per year and a high temporal-resolution NDVI annual profile. Gottschalk et al. (2005) found that multi-temporal images had better discriminatory power than single-date images for detecting wildlife-habitat relationships. MODIS also provides spectral reflectance values for 36 spectral bands whereas comparable models such as Landsat only provide information at 7–8 spectral bands. Lastly, the MODIS data are free and available to the public.

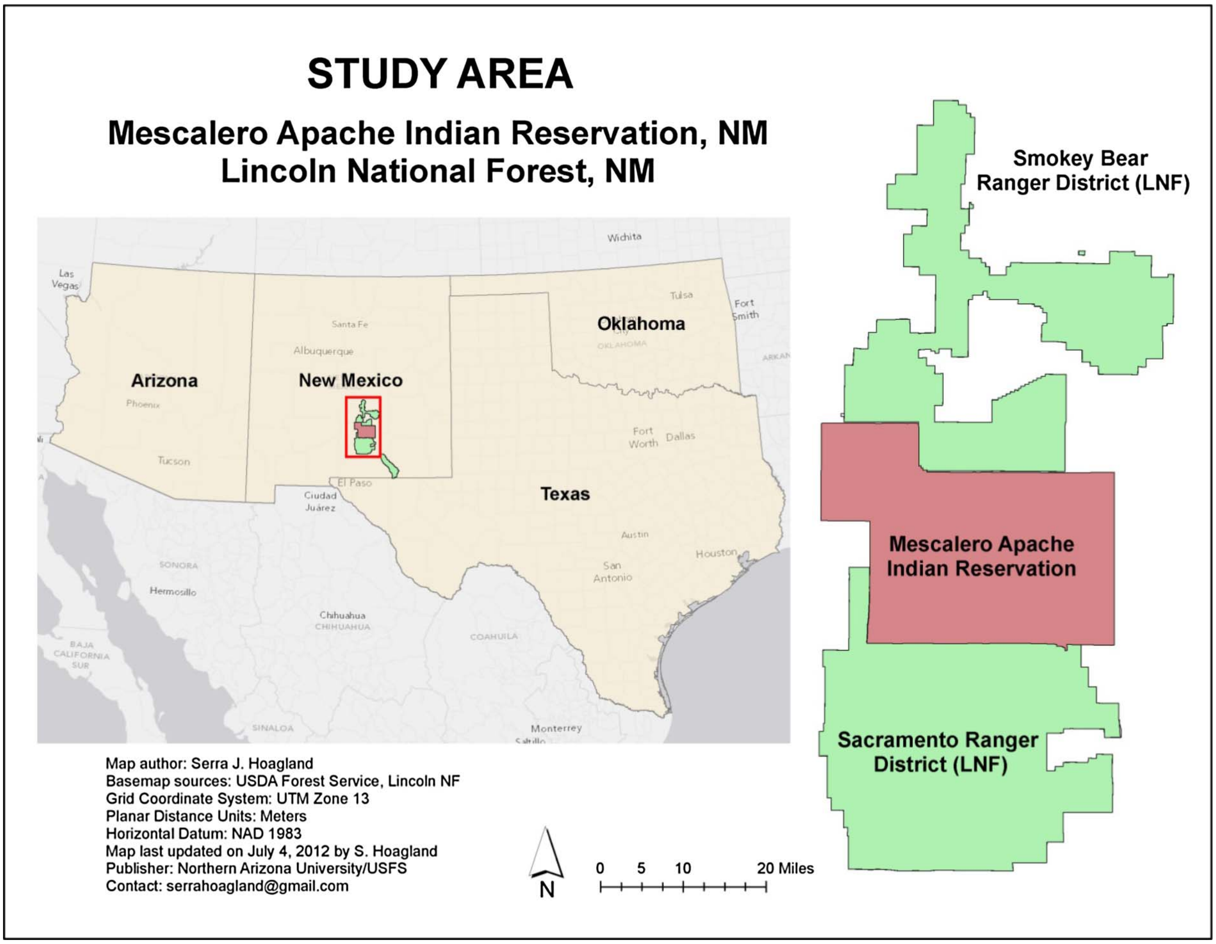
2.2. Phenoclasses

The US Forest Service Eastern Forest Threat Assessment Center (EFETAC) in collaboration with Oak Ridge National Laboratory and NASA Stennis Space Center (hereafter "EFETAC team") created phenoclass types using k-means clustering techniques described in Hargrove et al. (2014), Hoffman et al. (2013), Hoffman et al. (2010), and White et al. (2005). The phenoclasses were developed for the entire United States at 5 thematic resolutions (100, 200, 500, 1000 and 5000 classes; Table 1). The classes were developed to detect and monitor forest change in areas without ground or aerial surveys (Norman et al., 2013; Mills et al., 2011; Hargrove et al., 2009). The classes were originally termed phenoregions in these publications, but, although it was made clear that they were not spatially contiguous, we rename them phenoclasses here to more explicitly emphasize that they are simply labels applied to given pixel-year combinations. We obtained the phenoclass datasets (Table 1) from the ForWarn (2016) database and Oak Ridge National Laboratory Distributed Active Archive Center (MODIS NDVI, no date).

Using MODIS imagery from 2000 to 2012, the EFETAC team first assigned pixel-year combination a phenoclass according to its annual NDVI profile. Then they assigned each 5.3 ha pixel to the phenoclass that occurred most frequently across the 13 year time period (Fig. 1). When 2 or more phenoclasses were tied for highest frequency, the pixel was assigned to the phenoclass with the highest sum of all 46 annual NDVI values (one every eight days); this sum is approximately proportional to gross primary production, and thus most likely to represent the least disturbed condition of that MODIS cell.

2.3. Phenoclusters

We used a k-means FASTCLUS procedure in SAS 9.4 to cluster sites based on the composition of the ten most common phenoclasses found within a fixed radius neighborhood of a site. The FASTCLUS iterative algorithm seeks to minimize the sum of squared distances from cluster



Map author: Serra J. Hoagland
Basemap sources: USDA Forest Service, Lincoln NF
Grid Coordinate System: UTM Zone 13
Planar Distance Units: Meters
Horizontal Datum: NAD 1983
Map last updated on July 4, 2012 by S. Hoagland
Publisher: Northern Arizona University/USFS
Contact: serrahoagland@gmail.com

Fig. 2. The study area spans over 566,560 ha and is located in south-central New Mexico within the Mescalero Apache Indian Reservation and two districts of the Lincoln National Forest (LNF).

means. We used this algorithm because it is fast and it can be applied to larger datasets (Jain et al., 1999). We set 10 as the maximum number of clusters after pilot runs showed anywhere from 4 to 7 cluster types using similar datasets, and set 20 as the maximum number of iterations for recomputing cluster seeds (initial centers of cluster values). Iterations were designed to delete clusters that had less than 10 sites assigned to that phenocluster, which was less than 5% of the total sample size. Every site was assigned to the nearest seed and the seeds were recomputed as the means of the clusters. The process repeated itself until it reached convergence and the root mean squared difference was at a minimum. Thus the iterative process selected the number of clusters to keep based on the most parsimonious set with greatest coverage. We employed the CANDISC procedure (canonical discriminant analysis) in SAS to assess the clustering process and identify if we were able to get good separation among the observations within the data space defined by the phenoclusters membership. The CANDISC procedure is related to canonical correlation and principal component analysis. It identifies linear combinations of the various phenoclass proportions that provide maximum separation between phenocluster groups and displays the orientation of data points in canonical space.

2.4. *Application to Mexican spotted owl habitat*

We applied these procedures to 566,560 ha of forest lands on the Mescalero Apache Indian Reservation and the adjacent Lincoln National Forest (LNF) in the Sacramento Mountains of south-central New Mexico (Fig. 2). The Sacramento Mountains support the highest density of Mexican spotted owls within the Basin and Range East Management

Table 1
Statistics describing phenoclasses in the Mescalero Apache Indian Reservation and the Lincoln National Forest in south-central New Mexico (total area = 13,077 km^2) at five thematic resolutions of the national classification of Normalized Difference Vegetation Index (NDVI) phenoclasses developed by Eastern Forest Environmental Threat Assessment Center (EFETAC) team.

	Phenoclass resolution (number of classes)				
	100	200	500	1000	5000
Number of phenoclasses in study area (% of national classes)	58 (58%)	99 (50%)	201 (40%)	340 (34%)	1147 (23%)
Number of phenoclasses required to comprise 100% of 211 Mexican spotted owl (MSO) sites (% of classes in study area)	42 (72%)	67 (68%)	115 (57%)	195 (57%)	517 (45%)
Number of classes required to comprise at least 80% of the 211 MSO sites (% of classes in study area)	4 (7%)	7 (7%)	12 (6%)	20 (6%)	66 (6%)
Area (km^2) of phenoclasses composing ~80% of MSO nesting habitat (% of study area)	1846 (14%)	2026 (16%)	1966 (15%)	2002 (15%)	2496 (19%)
Cumulative proportional area of MSO sites of the top 4 phenoclasses	83%	69%	55%	33%	19%

Unit, one of 6 Units designated in the recovery plan for the owl (USFWS, 2012). Elevations vary from 1200 m to 3650 m with steep slopes on the western ridge and more gradual slopes on the east slope. Average annual rainfall is approximately 64 cm/year, most of which occurs as rain from July through September, and mean annual temperature is 10 °C (Mexican Spotted Owl Management Plan for the Mescalero Apache Reservation, 1998). There were about 140 Mexican spotted owl Protected Activity Centers on the Lincoln National Forest and about 71 owl territories on Mescalero.

Because owls probably do not select breeding sites based solely on conditions in a single 5.3-ha pixel but rather assess habitat in the neighborhood around a potential site as well, we defined an owl site as a roughly circular area of about 1 km radius, and used this radius to define phenocluster neighborhoods. Because pixel boundaries did not form perfect circles, each site consisted of 57 MODIS pixels that were closest to the center point. Other studies (Bond et al., 2009; Jenness et al., 2004; Bond et al., 2002b; Andries et al., 1994) also used a distance of 1 km radius as the survey area for Mexican spotted owls or other bird species. A 1 km radius approximates the area of a Protected Activity Center (USFWS, 2012; USFWS, 2011; USFWS, 1995) and Mexican spotted owls will forage within this area during the breeding season (Peery et al., 1999).

The center of each owl site was either a Mexican spotted owl nest (Mescalero nest sites) or the center of a Protected Activity Center (LNF nest sites). On Mescalero, nest locations were obtained from the Mescalero Apache Indian Tribal Division of Resource Management and Protection (DRMP) and the Bureau of Indian Affairs (BIA) Mescalero Agency. Nests were located between early-May to late-June using well-established techniques (USFWS, 2012; Franklin et al., 1996; Forsman, 1983) under USDI FWS Permit TE26800B-0, USDI FWS Permit TE040346-0 and the Mescalero Apache Tribal Resolution 12-50 (2012). If multiple nest sites for a single territory at Mescalero were defined (i.e. from historical nests), we used the most recent nest location as the center. If the nest tree was not identified, we used juvenile roost locations found prior to August 1 during the most recent year as the center (Ward and Salas, 2000).

Because owl nest locations were not readily available for the Lincoln National Forest, we used the geometric center of the core area as the center point. We obtained core and Protected Activity Center (PAC) boundaries from the LNF Geographic Information Systems (GIS) wildlife geospatial online database (LNF GIS database). If two cores were delineated for a single breeding territory on the LNF we selected the geometric center of the largest core area as the center point.

2.5. Habitat selection

We generated two thousand random points and sites, each centered on a point randomly placed in forest overstory types that owls were known to nest in within our study area. Random points were placed in aspen, pine mixed, ponderosa pine, mixed-conifer, Douglas-fir, oak and spruce fir forest types as mapped in the Reservation Timber Type map provided by the Mescalero DRMP; and in aspen, mixed-conifer/aspen, mixed-conifer, oak and ponderosa pine forest types as mapped in the LNF Terrestrial Ecological Unit (TEU) forest vegetation shapefile. A minimum distance of 500 m was set between points to ensure that center pixels were sampled no more than once. The ultimate purpose of the random point sampling was to provide a basis for comparison that has the same spatial sampling structure as the observed owl sites. This is not a measure of the total frequency of the entire landscape, nor is it a measure of the individual phenoclass composition within known suitable habitat. Rather it is the distribution one would expect if the owl sites were randomly located within the previously designated suitable habitat types. All random point locations and Mexican spotted owl point locations were converted in GIS into Lambert Azimuthal Equal-Area projection to match the projection of the phenoclass datasets. Each random site was a roughly circular area consisting of 57 MODIS pixels that were entirely or mostly within the 1 km radius.

Overall owl selectivity was calculated for phenoclasses from the 100 phenoclass resolution found in highest proportion in Mexican spotted owl sites by taking the percentage of the area within a 1 km neighborhood within 211 owl sites and dividing it by the percentage of the same neighborhood around 2000 random points. This approximately reflects a used/available (owls/random) proportion (Poulin et al., 2008; Bond et al., 2002a), where values < 1 indicates lower preference or less suitable and values > 1 indicate some degree of preference or suitability. Owl selectivity was also calculated by ownership and by individual phenocluster type. Two tailed z tests were used to make inferences about the difference between the two population proportions (Ott and Longnecker, 2010) for the owl selectivity values among ownerships.

2.6. Habitat suitability mapping

To create habitat suitability maps for the entire study region, we first conceptualized the four predominant phenoclusters associated with used owl sites as four types of forest settings suitable for spotted owl breeding. We then created a continuous habitat suitability map by comparing every possible neighborhood with these four dominate phenoclasses. To do so, we summarized the composition of phenoclasses in the 57 pixels nearest to every pixel in the landscape using a moving window approach. We then quantified the degree of similarity between every neighborhood with each of the four suitable spotted owl phenoclusters in order to produce a continuous habitat suitability map. Habitat suitability was thus defined as the minimum distance (in phenocluster compositional space) from each moving window to the centroids of the 4 phenoclusters that characterized all Mexican spotted owl sites. We then used a color gradient to map the habitat suitability for each pixel in the landscape. This map reflects the relative similarity to current Mexican spotted owl nesting sites of the neighborhood surrounding each pixel. This map is a culmination of both the phenoclass analysis as well as the phenoclusters analysis.

2.7. Associating phenoclasses with owls

For the phenoclasses that were most abundant at Mexican spotted owl sites, we mapped their abundance and spatial distribution in the landscape, inferred the relative dominance of deciduous and/or evergreen vegetation from the annual NDVI profile (Gamon et al., 1995, Reed et al., 1994), and visited and characterized stand structure and composition by conducting stand exams in dominant phenoclasses (Table 2 and Hoagland, 2016). Evergreen patterns are reflected by high NDVI values throughout the year indicating relatively green vegetation despite the changing seasons. Conversely, deciduous vegetation has an NDVI profile that peaks during the growing season, with relatively lower NDVI values as the trees lose their leaves in the winter months (Reed et al., 1994). We collected the NDVI values from the original algorithms to graph the rescaled annual NDVI profile for the top 5 occurring phenoclasses within the 100 class dataset (Fig. 3). We used the 100 phenoclass dataset as an example for simplicity. Phenoclasses were originally given an arbitrary numerical label, such as ranging from 1 to 100. We reassigned each of the top 5 occurring phenoclasses within the 100 class an identifier (Table 2) that reflected its NDVI signal (Norman et al., 2013; Reed et al., 1994) followed by the dominant tree species by basal area, namely Evergreen white fir (*Abies concolor*) (EV-WF), Evergreen Douglas-fir (*Pseudotsuga menziesii*) (EV-DF), Evergreen dry mixed conifer (EV-DMC), Deciduous Douglas-fir/white fir (DC-DFWF) and Deciduous Douglas-fir/ponderosa pine (DC-DFPP) (Table 2).

We collected stand exam and canopy cover data in a total of 83 vegetation plots on the Reservation (methods and descriptive statistics can be found in detail in Hoagland, 2016) to describe stand structural conditions in the dominant phenoclass types found within Mexican

Table 2

Selectivity and vegetation characteristics of the 5 dominant phenoclasses found in highest proportion in Mexican spotted owl sites for the 100 phenoclass thematic resolution. Classes are generally listed in rank order from highest to lowest mean NDVI (Fig. 3). Phenoclass numbers are arbitrary (the values provide no ecological information). The first two letters of the identifier indicates the dominant NDVI phenological signature as either evergreen (EV) or deciduous (DC), and is followed by a code for the dominant tree species by basal area in the inventory plots (WF = White fir (*Abies concolor*), DF = Douglas-fir (*Pseudotsuga menziesii*), DMC = Dry mixed conifer, DFWF = Douglas-fir/White fir mix, DFPP = Douglas-fir/Ponderosa pine *Pinus ponderosa* mix). The selectivity is the proportion of area within a 1 km neighborhood around owl sites in that phenoclass divided by the proportion of area within the same neighborhood around the random points (the ratio of the previous 2 columns). Thus selectivity values > 1 indicate strong preference, values < 1 indicate lower preference, and values close to 1 indicate that owls use the class in proportion to availability on the landscape. General stand conditions and vegetation characteristics were derived from stand exam data including but not limited to: total live basal area and the total basal area (live + dead), QMD (Quadratic Mean Diameter), tree density, and canopy cover.

Phenology		Overall study area			Tribal lands			Lincoln National Forest			Vegetation characteristics				
Phenoclass	Identifier	% of area around 211 owl sites	% of area around 2000 random points	Selectivity	% of area around owl sites (n = 71)	% of area around random points (n = 814)	Selectivity	% of area around owl sites (n = 140)	% of area around random points (n = 1186)	Selectivity	# veg plots	General stand description (Hoagland, 2016) Tree species listed in order of percentage of basal area.	Total live basal area m^2/ha (Total basal area = live + dead) [ft^2/ac] see Supplemental Material	Trees per ha (Trees per acre)	Average % canopy cover
96	EV-WF	18.1	7.7	2.34	9.7	3.8	2.55	22.4	10.4	2.15	5	Dominated by evergreen phenological signature: 48% White fir, 23% Douglas-fir. QMD = 30.2 cm	16.5 (39.0) [71.9 (170.1)]	160 (396)	52.5
56	EV-DF	40.1	22.5	1.78	45.2	20.8	2.17	37.5	23.7	1.58	43	Dominated by evergreen phenological signature: 35% Douglas-fir, 22% White fir. QMD = 25.4 cm	26.9 (34.1) [117.2 (148.5)]	158 (391)	53.4
59	EV-DMC	17.5	18.5	0.95	24.4	21.8	1.12	14.0	16.2	0.86	24	Dominated by evergreen phenological signature: stands composed primarily of dry mixed conifer species: Douglas-fir, Alligator juniper, white fir, southwestern white pine, Gambel oak, and pinyon pine, etc. QMD = 21.6 cm	24.4 (33.3) [106.3 (145.2)]	230 (569)	48.6
35	DC-DFWF	7.1	4.8	1.48	8.4	4.7	1.78	6.5	4.9	1.33	6	Dominated by deciduous phenological signature: stands composed primarily of Douglas-fir, white fir and relatively lower total basal area. QMD = 27.9 cm	14 (26.6) [60.8 (116)]	100 (247)	47.6
87	DC-DFPP	5.3	7.8	0.68	5.8	10.2	0.57	5.1	6.2	0.82	5	Dominated by deciduous phenological signature: stands composed primarily of Douglas-fir, ponderosa pine, and Gamble oak with relatively lower total basal area. QMD = 19.8 cm	20.4 (30.1) [88.9 (131.2)]	214 (528)	31.8

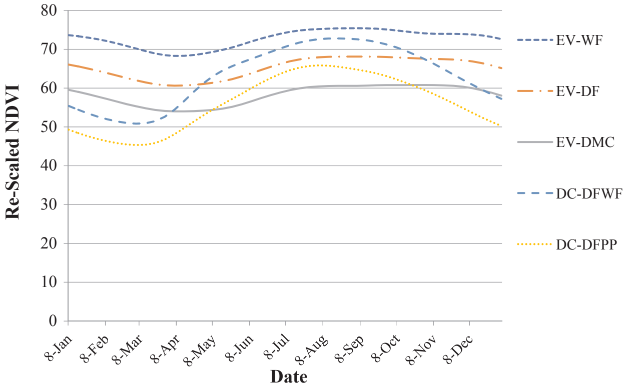


Fig. 3. Annual Normalized Difference Vegetation Index (NDVI) signatures of the five dominant phenoclasses (Table 2) in the 100 phenoclass thematic resolution, found in highest proportion within a 1-km radius buffer of known Mexican owl sites on the Reservation and on the Lincoln National Forest. Evergreen white-fir (EV-WF) has a consistent NDVI pattern throughout the year and also exhibits the highest overall NDVI value whereas deciduous Douglas-fir ponderosa pine (DC-DFPP) has a distinct peak in the growing season and lowest NDVI values throughout the year, which indicates lower total basal area and relatively larger influence of deciduous vegetation.

spotted owl breeding sites. In addition to other stand level metrics the total live and dead basal area by species and by size class for the dominant phenoclass types was calculated using Field Sampled Vegetation Database (FSVeg) modules using the non-weighted method. We tabulated and summarized the phenoclass composition of each owl site and random site. We compared phenoclass compositions between groups (used versus random, LNF versus Mescalero) and affirmed the significance of the differences using a simple chi-squared analysis.

3. Results

We analyzed 211 owl sites within the study region; approximately one third of these sites were on the Reservation and the remainder were within the boundaries of the Lincoln National Forest. The percentage of phenoclasses needed to comprise > 80% of the Mexican spotted owl used sites decreased with increasing thematic resolution (Table 1). This is likely due to the higher precision in delineation of various NDVI signals at higher thematic resolutions and reflects the ability of the k-means clustering algorithm to detect finer-scale differences in NDVI seasonal patterns at higher resolutions (W. Hargrove, personal communication), producing a more specific view of the landscape as thematic resolution increases (Benson and MacKenzie, 1995). However, when considering the number of phenoclasses that compose owl habitat out of the entire dataset that fell within our study region the trend stayed relatively stable with increasing thematic resolution at approximately 6%. There was an exponential decline in the cumulative proportional area of owl sites covered by the top 4 phenoclasses (Table 1), which is further evidence of increased specificity or landscape pixelation as the number of phenoclass increased. Mexican spotted owls consistently occupied a small fraction of the area of the landscape (14–19%) and an even smaller fraction of the available habitat types within the landscape (approx. 6%), which is consistent with previous studies classifying Mexican spotted owls as habitat specialists (Ganey and Dick, 1995).

Annual NDVI signatures of the top 5 phenoclasses from the 100 phenoclass thematic resolution (Fig. 3 and Table 2) indicate that both evergreen and deciduous tree species compose Mexican spotted owl breeding habitat. These include evergreen Douglas-fir (EV-DF) at 40% composition, evergreen white fir (EV-WF) at 18% composition, evergreen dry mixed conifer (EV-DMC) at 17% composition, deciduous Douglas-fir/white fir (DC-DFWF) at 7% composition and deciduous Douglas-fir ponderosa pine (DC-DFPP) at 5.3% composition (Table 2 and Supplemental Material A). EV-WF had the highest NDVI values that were relatively constant throughout the year (flat NDVI profile; Fig. 3). EV-DF had slightly lower NDVI values than EV-WF but also remained relatively constant throughout the year. EV-DMC had the lowest of the evergreen signals but did not show a distinct peak in the growing season. DC-DFWF showed a peak in NDVI values starting in early April and lasting approximately through early November. DC-DFPP had lower NDVI values than DC-DFWF but also exhibited a peak in the growing season similar to DC-DFWF.

The composition of phenoclasses in owl sites differed from the composition of phenoclasses in random points in suitable forest cover types (Chi-squared test, $p < .05$) at all 5 thematic resolutions (Table 2; Supplemental Material A). For instance, for the 100 phenoclass thematic resolution, approximately 40% of the combined owl sites were type EV-DF and only 23% of the area within a 1-km radius buffer around random points were EV-DF. Further, 18% of owl habitat was EV-WF while only 7% of the random points placed in suitable habitat were delineated as such.

Phenoclass selectivity values for the entire study region ranged from 0.68 (least preferred or unsuitable) to 2.34 (strongest preferred), for DC-DFPP and EV-WF respectively. EV-DF ranked as second highest preferred phenoclass among all sites (1.74). Within owl neighborhoods, the rank order of preference was nearly identical on the Reservation and LNF lands. For owl sites on the Reservation and the LNF selectivity was strongest for EV-WF and lowest for DC-DFPP. A notable difference in selectivity between the Reservation and the LNF was for EV-DMC, this phenoclass was moderately selected for on the Reservation (1.12) and less selected for on the LNF (0.86). Although not statistically significant ($p > 0.2$), selection indices for “preferred” phenoclasses were greater (higher total maximum value and higher mean) on the Reservation. The selectivity values on the Reservation ranged from 0.57 to 2.55 (difference = 1.98) and 0.82–2.15 (difference = 1.33) on the LNF. Random and owl sites were ranked by percent area for each ownership in Table 3 and indicated relatively similar rankings between owl use on the Reservation and the Lincoln National Forest. However, the rankings were different for the random points on the Reservation versus random points on the Lincoln National Forest (Table 3).

Stand descriptions of each phenoclass can be found in Table 2 and tree species are listed in percentage of the total basal area as applicable to describe the general species composition (see Hoagland, 2016 for

Table 3
Rank ordering of values by ownership for the top 5 phenoclasses found in highest proportion within owl neighborhoods. Owl and random sites are ranked by percent area for each ownership. Rankings were relatively similar for owl use on the Reservation and the Lincoln National Forest. However, the rankings were completely dissimilar for the random points on the Reservation versus random points on the Lincoln National Forest.

		Reservation		Lincoln National Forest	
Phenoclass	Overall selectivity	Owl (used)	Random (available)	Owl (used)	Random (available)
Evergreen White fir (EV – WF)	1	3	5	2	3
Evergreen Douglas fir (EV – DF)	2	1	2	1	1
Deciduous Douglas fir/White fir (DC – DFWF)	3	4	4	4	5
Evergreen Dry Mixed Conifer (EV – DMC)	4	2	1	3	2
Deciduous Douglas fir/Ponderosa Pine (DC – DFPP)	5	5	3	5	4

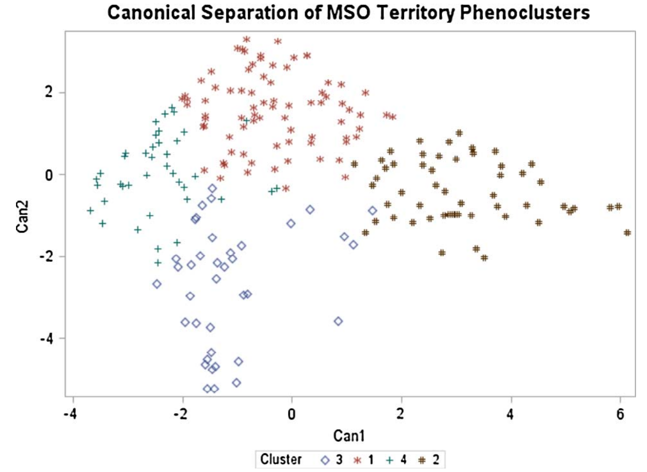


Fig. 4. The CANDISC procedure was run in SAS to inspect Mexican spotted owl phenocluster assignment from the FASTCLUS procedure. This scatterplot shows the separation of 4 Mexican spotted owl phenoclusters types in canonical space.

methods). Using data from representative vegetation stand exams when visited on the ground total live basal areas ranged from a minimum of 14 m^2/ha for DC-DFWF to a maximum of 27 m^2/ha in the EV-DF phenoclass (mean = 20.4 m^2/ha). EV-WF had the highest amount of recent mortality (57.7% of total basal area) while EV-DF had the lowest amount of recent mortality (21% of total basal area). Percent canopy cover was lowest for DC-DFPP than all other phenoclasses. Percent canopy cover was highest for EV-DF.

A convergence criterion was satisfied during the FASTCLUS procedure and Mexican spotted owl territories throughout the study region clustered into 4 distinct phenoclusters (Fig. 4). Mexican spotted owl cluster type 1 was approximately 64% EV-DF, while owl cluster type 2 was 51% EV-WF (Table 4). Cluster type 3 was a mix of phenoclass compositions while owl cluster type 4 was 30% EV-DF and 53% EV-DMC, with little representation from EV-WF. We calculated the number of owl sites for the entire landscape and for each ownership that fell into each phenocluster type. A majority (48%) of the owl sites on the Reservation fell into phenocluster type 1 whereas owl sites on the LNF fell into phenocluster type 2 (33%). There was a stronger selectivity for phenocluster type 1 on the Reservation (2.09) versus the Lincoln National Forest (1.52). Also, the range of selectivity values was larger for the Reservation (difference = 1.83) than for the Lincoln National Forest (difference = 0.93) possibly indicating more homogenous conditions in available suitable habitat on the Lincoln National Forest.

The overall spatial distribution of phenoclasses that composed 80% of pixels within a 1 km radius of Mexican spotted owl sites at each of the 5 levels of thematic resolution remained relatively constant with increasing levels of thematic resolution (Fig. 5). Larger patch sizes of phenoclasses were found at lower thematic resolutions (i.e. 100 phenoclasses) than at higher resolutions (i.e. 5000 phenoclasses) around Mexican spotted owl sites (see bottom left panel Fig. 5). The total cumulative area of the top phenoclasses that composed 80% of pixels within a 1-km radius around Mexican spotted owl sites increased from 1846 km^2 at the 100 phenoclasses to 2496 km^2 at the 5000 phenoclasses.

The map of the 5 phenoclasses found in highest proportion within owl sites (Fig. 6) coarsely defines regions within our study site with NDVI annual profiles that are found in most owl sites. The area in these 5 phenoclasses (2118 km^2) is about 20% less than the area (2655 km^2) in the forest types used by owls (Fig. 6.). Interestingly, EV-WF and EV-DF were most strongly selected for and are within the interior regions of the Lincoln National Forest and Reservation (shown as red and orange areas on the map). Whereas DC-DFPP, which was consistently selected against, exists primarily on the fringes of the study area (shown as purple in Fig. 6.).

The composition of phenoclasses that composed at least 1% of habitat around owl sites on the Reservation (observed) differed (Chi-square = 20.9, df = 8, $p = .007$) from the composition of phenoclasses around owl sites on adjacent Lincoln National Forest lands (expected) for the 100 phenoclass resolution (Fig. 7). Trends were similar at all levels of thematic resolution (200, 500, 1000, and 5000; see Hoagland, 2016). For the 100 phenoclass classification, EV-DF composed 45% of the area in owl sites on the Reservation compared to 37% of the area in owl sites on the Lincoln National Forest. Conversely, only 10% of the area within a 1-km radius of owl sites on the Reservation were EV-WF whereas 22% of Lincoln National Forest habitat was classified as such. Overall, Mexican spotted owl sites on the Reservation have higher composition of Douglas-fir stands and dry mixed conifer. Whereas the Lincoln National Forest owl sites have a higher proportion of closed canopy white fir species and may be generally referred to as a wet mixed conifer system.

There was a significant difference (Chi-square = 53.5, df = 3, $p < .001$) between the proportion of Mexican spotted owl sites classified into each cluster on the Reservation compared to the Lincoln National Forest (Fig. 8). Thirty-two percent of sites on the Lincoln National Forest were clustered into owl cluster type 1, whereas almost half of the sites on the Reservation fell into this category. Similarly, only twelve percent of Mexican spotted owl sites on the Lincoln National Forest fell into cluster type 4 whereas 31% of Mexican spotted

Table 4
Number of owl sites within each phenocluster type as well as number of random points within each phenocluster type by ownership. Owl selectivity is broken down by ownership and is a ratio of the percentage of owl/random. Average percentages of the five dominant phenoclasses (identifiers from Table 2) in each of the 4 phenoclusters as indicated from the FASTCLUS procedure. Each phenocluster is defined by the phenoclass composition within 1 km radius circular owl sites.

	Owls			Random			Percent Phenoclass contribution to Phenocluster type					Owl selectivity by phenocluster type (owl/random)		
Phenocluster	Number of owl sites for entire study area (% of total n = 211)	Number of owl sites for Tribal lands (% of total n = 71)	Number of owl sites for LNF lands (% of total n = 140)	Number of random points (% of total n = 2000)	Number of random points for Tribal lands (% of total n = 814)	Number of random points for LNF lands (% of total n = 1186)	EV-DF	EV-WF	EV-DMC	DC-DFWF	DC-DFPP	Overall owl selectivity	Tribal[ǂ]	LNF[ǂ]
1	79 (37%)	34 (48%)	45 (32%)	427 (21%)	183 (23%)	244 (21%)	64.3	10.5	12.6	6.6	3.6	1.76	2.09	1.52
2	54 (26%)	8 (11%)	46 (33%)	332 (17%)	52 (6%)	280 (24%)	28.0	51.2	3.4	8.4	2.5	1.53	1.83	1.38
3	38 (18%)	7 (10%)	31 (22%)	756 (38%)	321 (39%)	435 (37%)	17.9	3.7	10.5	11.6	12.8	0.47	0.26	0.59
4	40 (19%)	22 (31%)	18 (13%)	485 (24%)	258 (32%)	227 (19%)	29.7	2.1	52.6	2.1	5.3	0.79	0.97	0.68
Overall owl selectivity							1.78	2.34	0.95	1.48	0.68			

[ǂ] 2 tailed z-test (alpha = 0.05) indicated no significant difference between selectivity as counts by phenocluster type among the different administrative units (*p-value* = .48 Phenocluster 1, *p-value* = .56 Phenocluster 2, *p-value* = .99 Phenocluster 3, *p-value* = .41 Phenocluster 4).

owl sites on the Reservation fell into this category. The Lincoln National Forest had higher proportions of Mexican spotted owl sites in cluster types 2 and 3 than the Reservation. The distributions of Mexican spotted owl clusters indicates a higher proportion of white fir and wet mixed conifer in owl sites on the Lincoln National Forest than the Reservation and higher proportion of Douglas-fir and dry mixed conifer in owl sites on the Reservation (Fig. 9).

The habitat suitability map (Fig. 9) shows relatively low suitability in the eastern portion of our study area, which is dominated by ponderosa pine and more open canopy woodlands. Areas of high suitability persist in the mid-elevations of the Sacramento Mountains that support a known high density of Mexican spotted owls. Relatively contiguous suitable habitat exists throughout the Reservation and the Smokey Bear and Sacramento Ranger Districts of the Lincoln National Forest. There is a drastic notable change from high suitability to low suitability on the western portion of the study area indicating the rapid change in elevation on the western slope of the mountain range; likely the leeward side for monsoonal rainfall. Conversely, there is a much more gradual transitional zone of high suitability to low suitability on the eastern portion of the study area that is attributed to the gradual change in elevation and forest types on the monsoonal windward side. Large open meadows or valleys are apparent within the Reservation where highways transverse the south central region and are shown as low suitability. Lastly, high alpine zones near Sierra Blanca Mountain in the northwestern portion of the Reservation indicate low suitability since this area is well above the tree line.

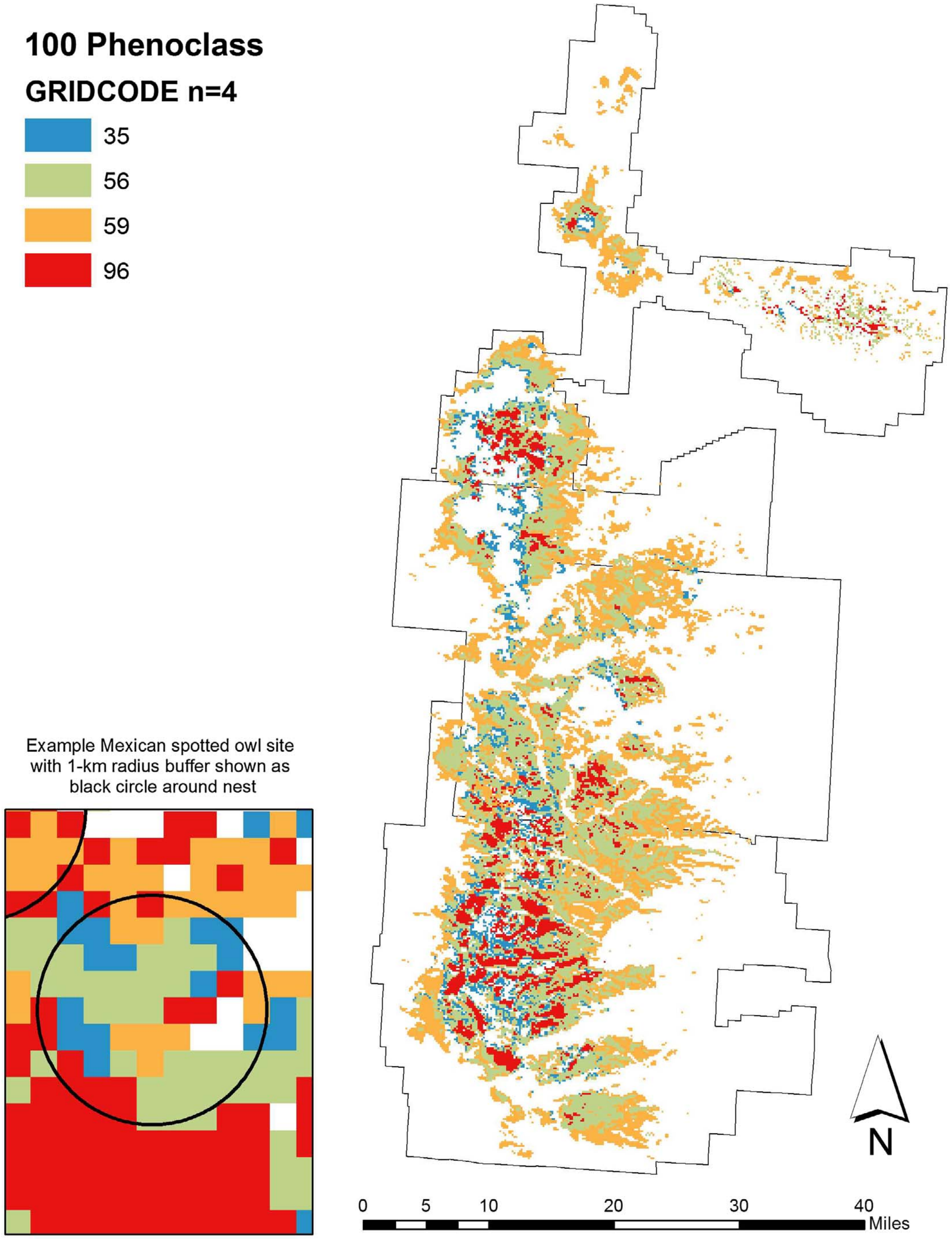


Fig. 5. Spatial distribution of phenoclasses that composed 80% of pixels within 1-km radius Mexican spotted owl sites each of 5 levels of thematic resolution.

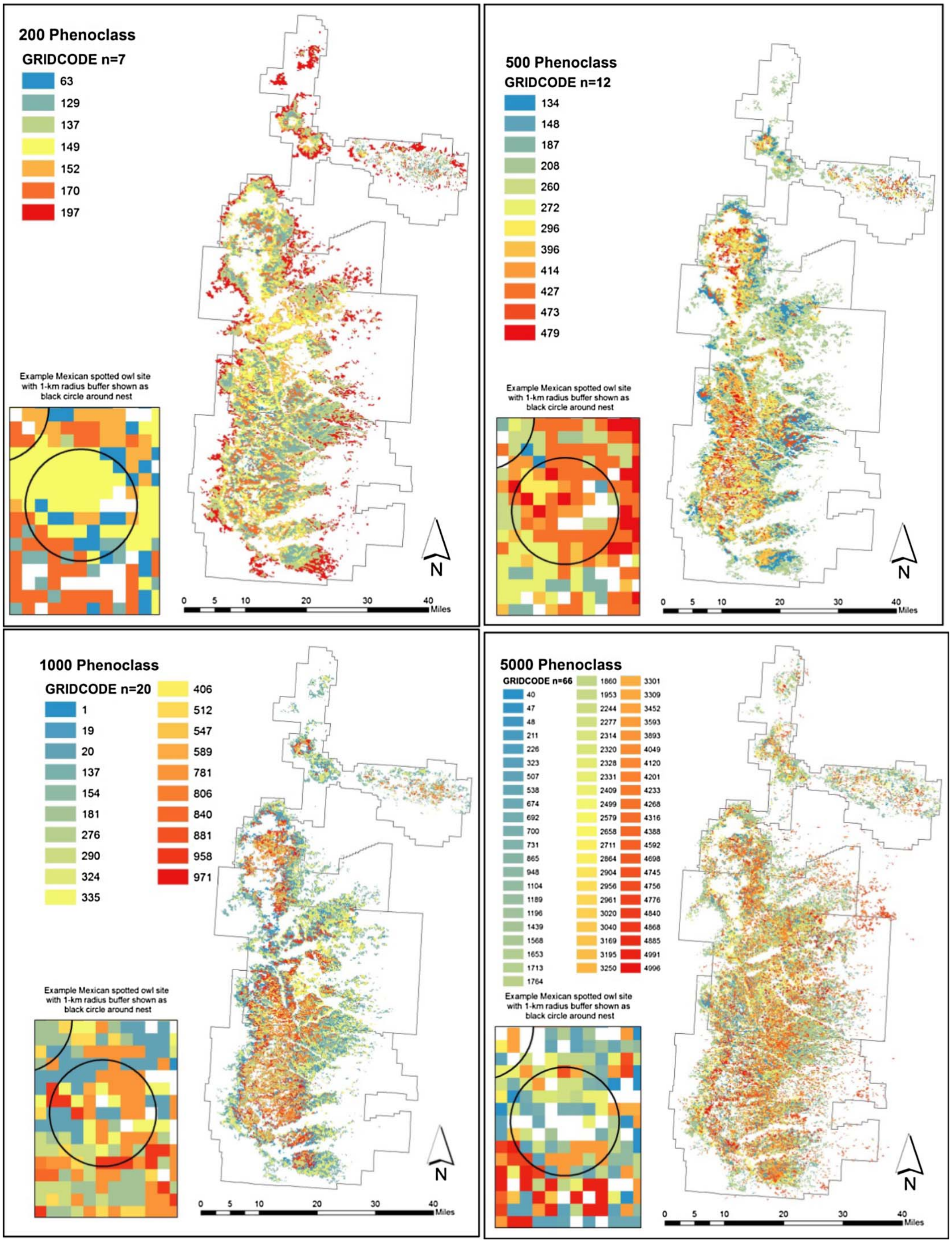
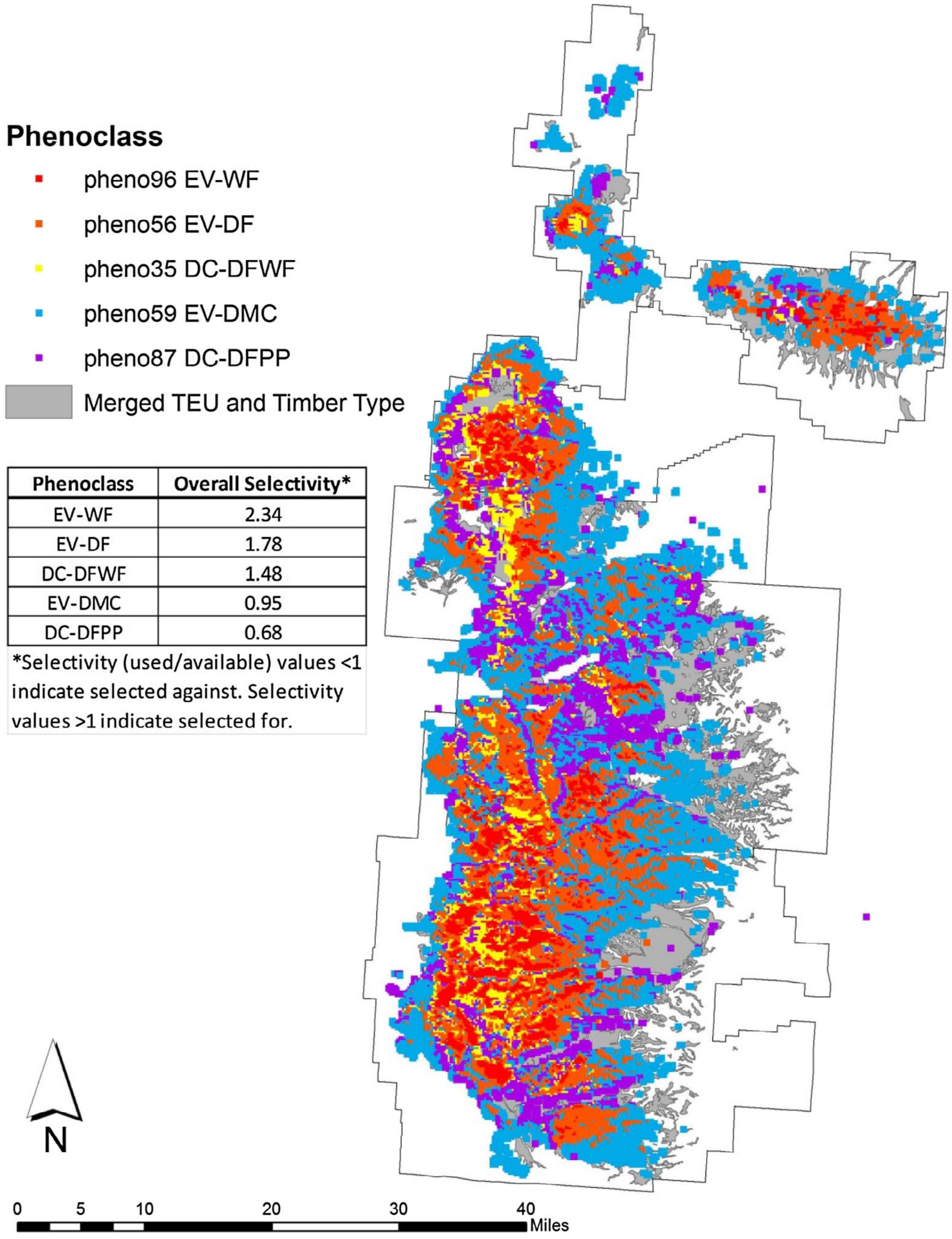


Fig. 5. (*continued*)

4. Discussion

At all five thematic resolutions tested the composition of phenoclasses around Mexican spotted owl sites differed from phenoclasses available in the study area. Therefore this approach of using nationwide phenoclasses and phenoclusters to generate habitat maps could be applied to other regions and species where presence data are available. Although it is not designed to identify microhabitat components such as snags, coarse woody debris, mistletoe platforms and other forest structural components important to Mexican spotted owls (Ganey et al., 2016; Ganey et al., 2013; May et al., 2004), and although MODIS pixel resolution (5.3 ha) is coarse, it proved useful for characterizing and comparing Mexican spotted owl habitat at landscape scale. In this paper we were primarily interested in whether or not we could rapidly assess and adequately detect places in the landscape that were suitable for owls without having to directly measure the microhabitat conditions.

Our habitat suitability maps were an improvement from using the timber type map polygons that were known to have Mexican spotted owl nests (Fig. 7). Other models for creating habitat maps for Mexican spotted owls include using timber type maps, Terrestrial Ecosystem Survey (TES) data and Landsat multispectral scanner imagery (ForestERA, 2005; Ganey and Benoit, 2002; Mellin et al., 2000; Ganey, 1991; Johnson, 1990; Johnson and Johnson, 1988). We believe our analysis is an improvement from these previous coarse-scale habitat models. MODIS' multi-temporal images have better discriminatory power than single-date images for detecting wildlife-habitat relationships (Gottschalk et al., 2005), especially for long-lived species with high site fidelity that may select habitat based on the conditions over



Phenoclass	Overall Selectivity*
EV-WF	2.34
EV-DF	1.78
DC-DFWF	1.48
EV-DMC	0.95
DC-DFPP	0.68

*Selectivity (used/available) values <1 indicate selected against. Selectivity values >1 indicate selected for.

Fig. 6. Spatial distribution of the top 5 phenoclasses (from the 100 phenoclass thematic resolution) found in highest proportion within a 1 km radius of known owl sites for the entire study area. The merged terrestrial ecological units (TEU) and Timber Type map for random sites is shown in background as grey polygon. Overall selectivity (used/available) is shown for each phenoclass. Warm colors denote higher Mexican spotted owl selectivity for nesting habitat and cooler colors denote lower selectivity.

several years (Zeng et al., 2010). Phenological shifts can occur within seasons and within years and are detected by MODIS NDVI and thus also by phenoclasses. Another major advantage to the MODIS imagery is that the phenoclass data are already collected, processed and are available to the public at no cost. This new rapid habitat assessment technique could be part of an effective approach to monitor wildlife habitat over large temporal and spatial scales.

Our methods identified a difference between owl breeding habitats on tribal versus off tribal lands. This indicates that current estimates of owl breeding habitat for the BREMU may be incomplete and including habitat assessments from tribal lands may create a better understanding of the range of habitat conditions. Our analysis indicated that Mexican spotted owl sites on the Reservation have higher composition of closed canopy Douglas-fir stands and dry mixed conifer whereas the Lincoln National Forest owl sites have a higher proportion of closed canopy white fir dominated stands and are possibly more indicative of a wet mixed conifer system. Although it is difficult to speculate and separate conflicting explanations for why there is more closed canopy white fir within owl sites on the Lincoln National Forest versus owl sites on the Reservation, two hypotheses are worth mentioning. First, the Lincoln National Forest owl sites are about 300 m higher in elevation and may experience more mesic conditions (higher snowfall and cooler climates) which can promote white fir. Or, this phenomenon could be attributed to natural stand dynamics and forest successional pathways where there has been a slow transition to white fir dominated stands in areas with little to no timber harvest and active fire suppression since white fir is slightly more shade tolerant than Douglas-fir (Minore, 1979; Jones, 1974; Tappeiner and Helms, 1971). Recent shifts in Southwestern mixed conifer forests include increases in basal area, tree density and a species compositional shift towards white fir as a result of fire suppression (Higgins et al., 2015; Mast and Wolf, 2004). In the multi-stand reports for EV-WF the live quadratic mean diameter (QMD) indicates that white fir trees are relatively small and are found at 71 trees/ha (176 TPA), which may indicate recent invasion. However within EV-WF there is a high amount of dead white fir with relatively larger QMD therefore perhaps the white fir component has always existed in the

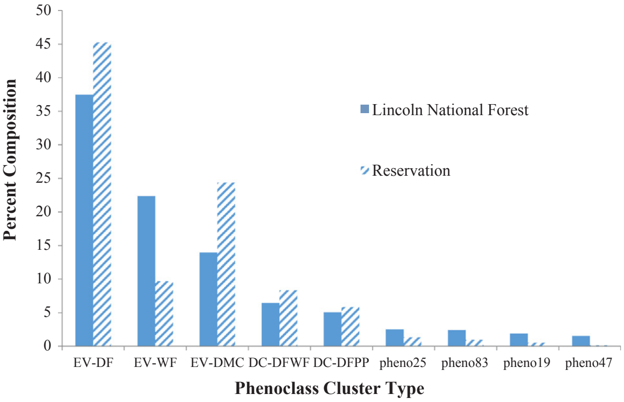


Fig. 7. Phenoclass composition within a 1-km radius buffer of known owl sites on the Reservation (n = 71) and owl sites on the Lincoln National Forest Smokey Bear and Sacramento Ranger Districts (n = 140). The Reservation owl sites had significantly higher proportions of EV-DF and EV-DMC than the Lincoln National Forest whereas the Lincoln National Forest owl sites had higher proportions of EV-WF than the Reservation.

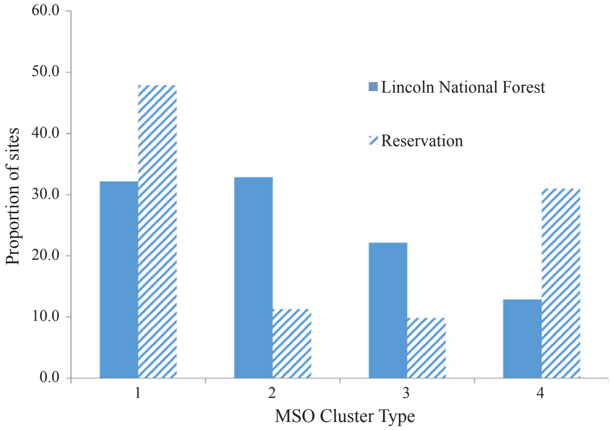


Fig. 8. Cluster type by ownership. There were significant differences (p-value $<$ .001) among Mexican spotted owl cluster types on the Reservation compared to the Lincoln National Forest. For instance, almost 50% of Mexican spotted owl sites on the Reservation were classified as Cluster type 1 whereas only 30% of Mexican spotted owl sites on the Lincoln National Forest were classified as such.

wetter mixed conifer sites and the difference is simply attributed to the variation in biogeographic conditions such as elevation and precipitation among ownerships.

Our results indicate that, despite the management differences between the Lincoln National Forest and the Reservation, suitable habitat is widely distributed throughout the Reservation even though it is structurally different from the Lincoln National Forest. Thus the tribe's use of sustained-yield timber management practices (most commonly applied are single tree selection and shelterwood with reserves practiced outside of owl core habitat) are likely consistent with managing for habitat conditions of the owl.

Annual NDVI signatures indicated a high level of evergreen tree species composition around Mexican spotted owl nest sites. White fir and Douglas-fir were commonly found as key habitat components in previous research on Mexican spotted owl nesting areas within our study site (Ganey et al., 2013; May et al., 2004). Previous findings indicate that Mexican spotted owls within our study region nest in predominately late successional mixed conifer forests at the bottom two-thirds of steep, north-east facing slopes in stands with high basal area (Ganey et al., 2013; May et al., 2004; Ganey and Balda, 1989). Our results are consistent with these previous findings. We observed that owls selected evergreen conditions with high photosynthetic activity, larger trees and relatively high basal area.

Unlike EV-WF, DC-DFWF and DC-DFPP phenological signatures had more signal of deciduous vegetation indicated by the peak in NDVI values during the growing season. DC-DFPP was found in lower proportions around owl sites compared to random points, indicating that owls have lower preference this phenoclass type. Further, DC-DFPP has the lowest NDVI values compared to the other top ranking phenoclasses. Although speculative, it is possible that these stands have undergone some degree of harvest or fuel reduction treatment indicated by the lower photosynthetic activity and lower basal area since several known patches of actively managed Douglas-fir stands exist near owl sites on the reservation. These stands are often managed for tee-pee pole production to support tribal members cultural need for smaller diameter Douglas-fir poles. More broadly, our conclusions support the notion of owls' slightly lower preference for open canopied, deciduous stands with lower basal area and thus lower total productivity. However, these deciduous stands were found within 1 km radius of current Mexican spotted owl breeding areas. Although we did not collect data on owl foraging behavior, it is possible these areas with lower tree density are serving for foraging habitat with more productive understory to support a higher density of prey communities (Converse et al., 2006). Although not used for nesting, DC-DFPP with higher xeric species composition on south and southwest facing aspects may be utilized during non-nesting seasons (Carey et al., 1992) or by other life phases of Mexican spotted owls, yet this was not tested in our analysis.

The larger range in selection values may indicate a broader range of selection preferences for available habitat types to owls on the Reservation and relatively more homogenous level of selection on the LNF. The selection gradient appears to parallel moisture gradient, from wettest (most preferred) to driest (least preferred). Rank ordering of owl use of phenoclasses was similar on the Reservation to the Lincoln National Forests, further encouraging and instilling more confidence in the phenoclass methods. However, there was a difference between the rank ordering of random sites on the Reservation and the Lincoln National Forest, indicating that the landscapes are different - yet the owl selection patterns remain relatively constant. Based on the selection indexes, owls in both ownerships prefer phenoclasses characterized by fewer larger trees. This is in agreement with numerous other spotted owl studies where roost sites contained a high proportion of residual ($>$ 100 cm DBH) trees (e.g. Moen and Gutiérrez, 1997, others).

We were able to characterize and compare Mexican spotted owl breeding habitat for this region using publicly available land surface phenology data. Owl habitat selectivity patterns were identified and owl habitat selection (by rank order) was similar among the two ownerships however the landscapes and selected habitat was fundamentally different. When coupled with stand level data, vegetation phenology patterns derived from remote sensing products identified structural differences between owl breeding sites on the Reservation to owl sites on the adjacent National Forest. This technology may be well suited for additional rapid wildlife-habitat assessments of broadly distributed species where presence data are available.

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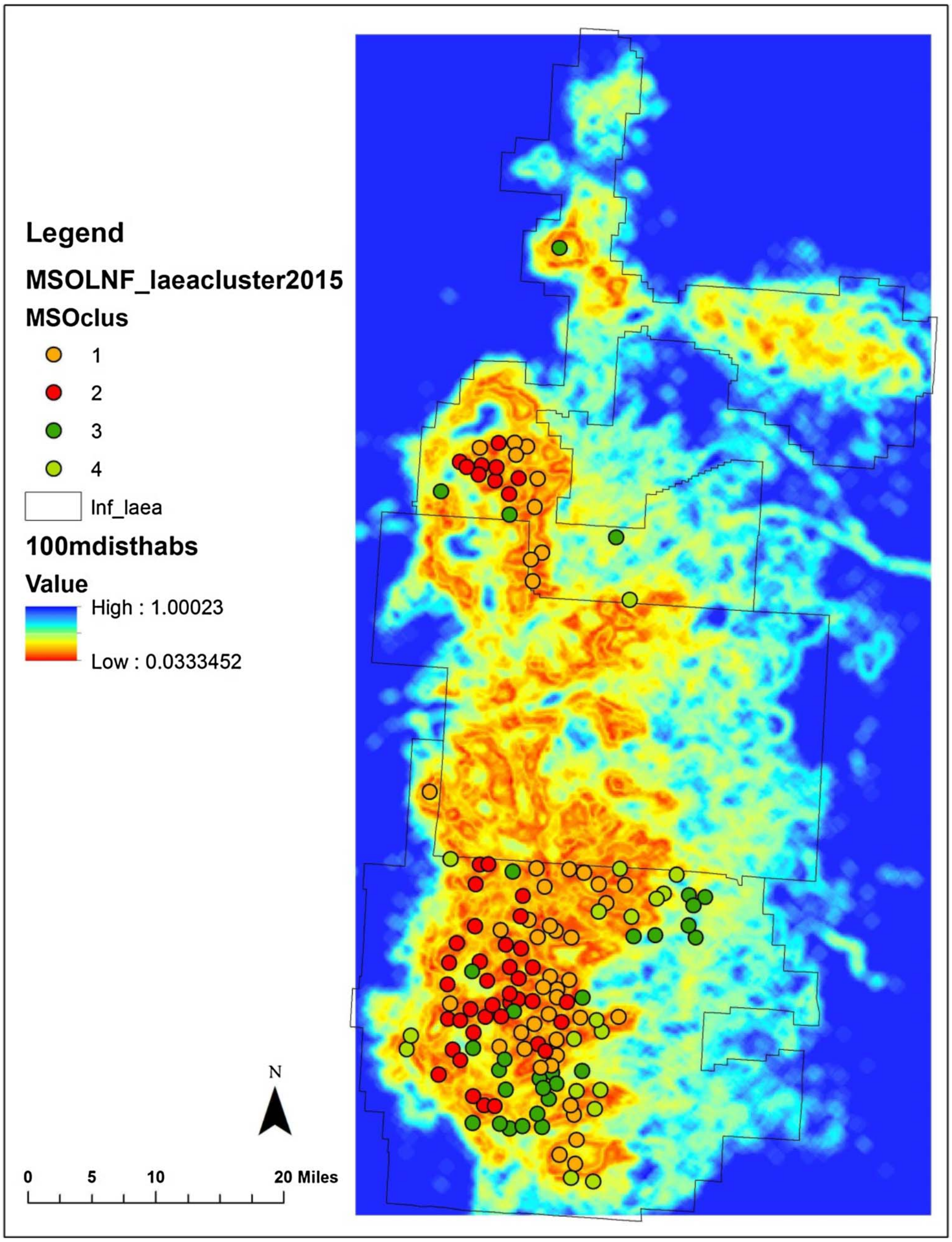

Fig. 9. Habitat suitability map based on minimum distance of each pixel to the centroid of most similar of the 4 phenoclusters preferred by Mexican spotted owls. Map also depicts the spatial distribution of Mexican spotted owl phenoclusters, which were clustered according to their phenological composition within a 1-km radius. Note: Mexican spotted owl clusters are not shown for the Reservation. Warm colors within the landscape denote high suitability (low minimum distance to nearest cluster centroid) and cooler colors denote low nesting habitat suitability (larger distance to nearest cluster centroid). Colors of Mexican spotted owl cluster symbols are arbitrary. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2017.12.017.

References

Andries, A.M., Gulinck, H., Herremanns, M., 1994. Spatial modelling of the Barn Owl *Tyto alba* habitat using landscape characteristics derived from SPOT data. Ecography 17, 278–287.

Archaeological Resources Protection Act of 1979. Available online at: < http://www.nps.gov/history/local-law/FHPL_ArchRsrcsProt.pdf> (last accessed on Feb. 26, 2016).

Bartel, R.A., Sexton, J.O., 2009. Monitoring habitat dynamics for rare and endangered species using satellite images and niche-based models. Ecography 32 (5), 888–896.

Benson, B.J., MacKenzie, M.D., 1995. Effects of sensor spatial resolution on landscape structure parameters. Landsc. Ecology 10, 113–120.

Bond, B.T., Burger, L.W., Leopold, B.D., Jones, J.C., Godwin, K.D., 2002a. Habitat use by cottontail rabbits across multiple spatial scales in Mississippi. J. Wildl. Manage. 66 (4), 1171–1178.

Bond, M.L., Gutierrez, R.J., Franklin, A.B., LaHaye, W.S., May, C.A., Seamans, M.E., 2002b. Short-term effects of wildfires on spotted owl survival, site fidelity, mate fidelity, and reproductive success. Wildl. Soc. Bull. 30 (4), 1022–1028.

Bond, M.L., Lee, D.E., Siegel, R.B., Ward, J.P., 2009. Habitat use and selection by California spotted owls in a postfire landscape. J. Wildl. Manage. 73 (7), 1116–1124.

Carey, A.B., Horton, S.P., Biswell, B.L., 1992. Northern spotted owls: influence of pretty base and landscape character. Ecol. Monogr. 62 (2), 223–250.

Cultural and Heritage Cooperation Authority from CFR25. Chapter 32A. Available online at: < http://uscode.house.gov/view.xhtml?path=/prelim@title25/chapter32A&edition=prelim > (last accessed on Feb. 26, 2016).

Converse, S.J., White, G.C., Block, B.M., 2006. Small mammal response to thinning and wildfire in Ponderosa pine-dominated forests of the Southwestern United States. J. Wildl. Manage. 70 (6), 1711–1722.

Forest Ecosystem Restoration Analysis Project [ForestERA], 2005. ForestERA Mexican spotted owl habitat layer—overview. Northern Arizona University. Available from: < http://forestera.nau.edu/data_overview.htm > .

Forsman, E.D., 1983. Methods and materials for locating and studying spotted owls. Gen. Tech. Rep. PNW-162. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, 8p.

ForWarn. Forest Change Assessment Viewer. USDA Forest Service. Available online at: < http://forwarn.forestthreats.org/fcav2/ > (last accessed on Mar. 1, 2016).

Franklin, A.B., Anderson, D.R., Forsman, E.D., Burnham, K.P., Wagner, F.W., 1996. Methods for collecting and analyzing demographic data on the northern spotted owl. Stud. Avian Biol. 17, 12–20.

Franklin, S.E., Hansen, M.J., Stenhouse, G.B., 2002. Quantifying landscape structure with vegetation inventory maps and remote sensing. Forest. Chron. 78 (6), 866–875.

Gamon, J.A., Field, C.B., Goulden, M.L., Griffin, K.L., Hartley, A.E., Joel, G., Peñuelas, J., Valentini, R., 1995. Relationships between NDVI, canopy structure, and photosynthesis in three Californian vegetation types. Ecol. Appl. 5 (1), 28–41.

Ganey, J.L. 1991. Developing and Testing a Predictive Model for Mexican Spotted Owl Habitat. Dissertation, Northern Arizona University. Flagstaff, Arizona, USA.

Ganey, J.L., Apprill, D.L., Rawlinson, T.A., Kyle, S.C., Jonnes, R.S., Ward, J.P., 2013. Nesting habitat of Mexican spotted owls in the Sacramento Mountains, New Mexico. J. Wildl. Manage. 77 (7), 1426–1435.

Ganey, J.L., Balda, R.P., 1989. Distribution and habitat use of Mexican spotted owls in Arizona. The Condor 91 (2), 355–361.

Ganey, J.L., Benoit, M.A., 2002. Using terrestrial ecosystem survey data to identify potential habitat for the Mexican spotted owl on national forest system lands: a pilot study. Gen. Tech. Rep. RMRS-GTR-86. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 25p.

Ganey, J.L., Dick, J.A., 1995. Habitat relationships of Mexican spotted owls: Current knowledge. Chapter 4:1–42 in: USDI Fish and Wildlife Service, Recovery plan for the Mexican spotted owl (Strix occidentalis lucida), Vol. II – Technical supporting information. USDI Fish and Wildlife Service, Albuquerque, New Mexico, USA.

Ganey, J.L., Inigues, J.M., Hedwall, S., Block, W.M., Ward, J.P., Jonnes, R., Rawlinson, R., Kyle, S.C., Apprill, D.L., 2016. Evaluating desired conditions for Mexican spotted owl nesting and roosting habitat. Forest Sci. 62 (4), 457–462.

Gillespie, T.W., Foody, G.M., Rocchini, D., Giorgi, A.P., Saatchi, S., 2008. Measuring and modeling biodiversity from space. Prog. Phys. Geogr. 32 (2), 203–221.

Goetz, S., Steinberg, D., Dubayah, R., Blair, B., 2007. Laser remote sensing of canopy habitat heterogeneity as a predictor of bird species richness in an eastern temperate forest, USA. Rem. Sens. Environ. 108, 254–263.

Gottschalk, T.K., Huettmann, F., Ehlers, M., 2005. Thirty years of analyzing and modelling avian habitat relationships using satellite imagery data: a review. Int. J. Rem. Sens. 26 (12), 2631–2656.

Hargrove, W.W., Kumar, J., Erguner-Baytok, Y., Hoffman, F.M., 2014. Predominant Environmental Factors Controlling and Predicting Phenological Seasonality Across the CONUS over the Last Decade. In: AGU Fall Meeting Abstracts, vol. 1, p. 03.

Hargrove, W.H., Spruce, J.P., Gasser, G.E., Hoffman, F.M., 2009. Toward a national early warning system for forest disturbances using remotely sensed canopy phenology. Photogramm. Eng. Rem. Sens. 75, 1150–2115.

Higgins, A.M., Waring, K.M., Thode, A.E., 2015. The effects of burn entry and burn severity on ponderosa pine and mixed conifer forests in Grand Canyon National Park. Int. J. Wildland Fire 24 (4), 495–506.

Hoagland, S.J., 2016. An Assessment of Mexican Spotted Owl (Strix occidentalis lucida) Habitat on Tribal and Non-tribal Lands in the Sacramento Mountain Range, NM. Northern Arizona University Dissertation, 226p.

Hoffman, F.M., Kumar, J., Hargrove, W.W., 2013. Integrating statistical and expert knowledge to develop phenoregions for the continental United States. In: AGU Fall Meeting Abstracts, vol. 1, p. 0490.

Hoffman, F.M., Mills, R.T., Kumar, J., Vulli, S.S., Hargrove, W.W., 2010. Geospatiotemporal data mining in an early warning system for forest threats in the United States. In: 2010 IEEE Geoscience and Remote Sens. Symposium (IGARSS), pp. 170–173.

Jain, A.K., Murty, M.N., Flynn, P.J., 1999. Data clustering: a review. ACM Comput. Surv. (CSUR) 31 (3), 264–323.

Jenness, J.S., Beier, P., Ganey, J., 2004. Associations between forest fire and Mexican spotted owls. Forest Sci 50 (6), 765–772.

Johnson, T.H., 1990. Revised timber type model of spotted owl habitat in northern New Mexico. Unpublished Report, Santa Fe National Forest, PO 43-8379-9-0664, New Mexico, USA, 10p.

Johnson, J.A., Johnson, T.H.,1988. Timber type model of spotted owl habitat in northern New Mexico. Unpublished Report, New Mexico Department of Game and Fish, Contract 516.6-75-18, Santa Fe, USA, 23p.

Jones, H.G., Vaughan, R.A., 2010. Remote Sensing of Vegetation. Oxford University Press, New York.

Jones, J.R., 1974. Silviculture of southwestern mixed conifers and aspen: the status of our knowledge. USDA Forest Service, Research Paper RM-122. Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO., 44p.

Kremer, R.G., Running, S.W., 1993. Community type differentiation using NOAA/AVHRR data within a sagebrushsteppe ecosystem. Rem. Sens. Environ. 46, 311–318.

Mast, J.N., Wolf, J.J., 2004. Ecotonal changes and altered tree spatial patterns in lower mixed-conifer forests, Grant Canyon National Park, Arizona, U.S.A. Landscape Ecol. 19 (2), 167–180.

May, C.A., Petersburg, M.L., Gutiérrez, R.J., 2004. Mexican spotted owl nest-and roost-site habitat in Northern Arizona. J. Wildl. Manage. 68 (4), 1054–1064.

McDermid, G.J., Franklin, S.E., LeDrew, E.F., 2005. Remote sensing for large-area habitat mapping. Prog. Phys. Geogr. 29 (4), 449–474.

Mellin, T.C., Krausmann, W.J., Clark, K.B., Enquist, C.F., 2000. Assessing gross changes within vegetation types associated with Mexican spotted owl habitat in New Mexico and Arizona. Pages unnumbered. In: Greer, J.D. (Ed.), Eighth Biennial Forest Service Remote Sensing Applications Conference, Albuquerque, New Mexico, USA. 12p.

Mescalero Apache Tribal Resolution, 2012. Mescalero, NM Resolution No. 12-50.

Mexican Spotted Owl Management Plan for the Mescalero Apache Reservation, 1998. Mescalero Apache Indian Reservation, NM.

Mills, R.T., Hoffman, F.M., Kumar, J., Hargrove, W.W., 2011. Cluster analysis-based approaches for geospatiotemporal data mining of massive data sets for identification of forest threats. Procedia Comput. Sci. 4, 1612–1621.

Minore, D., 1979. Comparative autecological characteristics of northwestern tree species-a literature review. USDA Forest Service, General Technical Report PNW-87. Pacific Northwest Forest and Range Experiment Station, Portland, OR, 72p.

MODIS NDVI Data, Smoothed and Gap-filled, for the Conterminous US: 2000–2013.

Moen, C.A., Gutiérrez, R.J., 1997. California spotted owl habitat selection in the central Sierra Nevada. J. Wildl. Manage. 1281–1287.

Morrison, M.L., Marcot, B., Mannan, W., 2012. Wildlife-habitat Relationships: Concepts and Applications. Island Press.

NASA. Earth Observatory System. Measuring Vegetation NDVI. Available online at: < http://earthobservatory.nasa.gov/Features/MeasuringVegetation/measuring_vegetation_2.php > (last accessed on Feb 17, 2016).

National Historic Preservation Act of 1966 as amended. Available online at: < http://www.achp.gov/docs/NHPA%20in%20Title%2054%20and%20Conversion%20Table.pdf> (last accessed on Feb. 26, 2016).

Norman, S.P., Hargrove, W.H., Spruce, J.P., Christie, W.M., Schroeder, S.W., 2013. Highlights of Satellite-Based Forest Change Recognition and Tracking Using the ForWarn System. Gen. Tech. Rep. SRS-180. Asheville, NC: US Department of Agriculture Forest Service, Southern Research Station, 30p.

Osborne, P.E., Alonso, J.C., Bryant, R.G., 2001. Modelling landscape-scale habitat use using GIS and remote sensing: a case study with great bustards. J. Appl. Ecol. 38, 458–471.

Ott, R.L., Longnecker, M., 2010. An Introduction to Statistical Methods and Data Analysis. Brooks/Cole, Cengage Learning, Canada, pp. 1273p.

Peery, M.Z., Gutierrez, R.J., Seamans, M.E., 1999. Habitat composition and configuration around Mexican spotted owl nest and roost sites in the Tularosa Mountains, New Mexico. J. Wildl. Manage. 63 (1), 36–43.

Poulin, J.F., Villard, M., Edman, M., Goulet, P., Eriksson, A., 2008. Thresholds in nesting habitat requirements of an old forest specialist, the Brown Creeper (Certhia americanan), as conservation targets. Biol. Conserv. 141 (4), 1129–1137.

Reed, B.C., Brown, J.F., Vanderzee, D., Loveland, T.R., Merchant, J.W., Ohlen, D.O., 1994. Measuring phenological variability from satellite imagery. J. Veg. Sci. 5, 703–714.

Sellers, P.J., 1985. Canopy reflectance, photosynthesis and transpiration. Int. J. Rem. Sens. 6, 1335–1372.

Sellers, P.J., 1987. Canopy reflectance, photosynthesis and transpiration II. Rem. Sens. Environ. 21, 143–183.

Shirley, S.M., Yang, Z., Hutchinson, R.A., Alexander, J.D., McGarigal, K., Betts, M.G., 2013. Species distribution modelling for the people: unclassified landsat TM imagery predicts bird occurrence at fine resolutions. Divers. Distrib. 1–12.

Sharik, T.L., Adair, W., Baker, F.A., Battaglia, M., Comfort, E.J., D'Amato, A.W., Delong, C., DeRose, R.J., Ducey, M.J., Harmon, M., Levy, L., Logan, J.A., O'Brien, J., Palik, B.J., Roberts, S.D., Rogers, P.C., Shinneman, D.J., Spies, T., Taylor, S.L., Woodall, C., Youngblood, A., 2010. Emerging themes in the ecology and management of North American forests. Int. J. Forest. Res. 2010, 11. http://dx.doi.org/10.1155/2010/964260. Article ID: 964260.

Tappeiner II, J.C., Helms, J.A., 1971. Natural regeneration of Douglas-fir and white fir on exposed sites in the Sierra Nevada of California. Am. Midl. Nat. 86 (2), 358–370.

Thibault, D., Chalifoux, S., Laperle, M., 1998. Using satellite imagery as a planning tool for Harlequin duck inventory. Int. J. of Remote Sensing 19, 5–9.

Tucker, C.J., Sellers, P.J., 1986. Satellite remote sensing of primary production. Int. J. Rem. Sens. 7, 1395–1416.

United Nations Declaration on the Rights of Indigenous Peoples. 2007. Articles 26, 29 and 31. Available online at: < http://www.un.org/esa/socdev/unpfii/documents/DRIPS_en.pdf> (last accessed on Feb. 26, 2016).

USFWS.S. Fish and Wildlife Service, 1995. Recovery Plan for the Mexican Spotted Owl: vol. 1. Albuquerque, New Mexico, 172p.

U.S. Fish and Wildlife Service, 2011. Draft Recovery Plan for the Mexican Spotted Owl (Strix occidentalis lucida), First Revision. U.S. Fish and Wildlife Service. Albuquerque, New Mexico, USA, 399p.

U.S. Fish and Wildlife Service, 2012. Final Recovery Plan for the Mexican Spotted Owl (Strix occidentalis lucida), First Revision. U.S. Fish and Wildlife Service, Albuquerque, New Mexico, USA, pp. 413.

USGS [US Geological Survey], 2011. Gap Analysis Program (GAP) National Land Cover, Version 2. Available at: < http://gapanalysis.usgs.gov/gaplandcover/data/ > (last accessed October 19, 2016).

Venier, L.A., Pearce, J., McKee, J.E., McKenney, D.W., Niemi, G.J., 2004. Climate and satellite-derived land cover for predicting breeding bird distribution in the Great Lakes Basin. J. Biogeogr. 31, 315–331.

Wallin, D.O., Elliott, C.C.H., Shugart, H.H., Tucker, C.J., Wilhelmi, F., 1992. Satellite remote sensing of breeding habitat for an African weaver-bird. Landscape Ecol. 7, 87–99.

Ward, J.P., Salas, D., 2000. Adequacy of roost locations for defining buffers around Mexican spotted owl nests. Wildl. Society Bull. 688–698.

White, M.A., Hoffman, F., Hargrove, W.W., Nemani, R.R., 2005. A global framework for monitoring phenological responses to climate change. Geophys. Res. Lett. 32 (4).

Zeng, Z.G., Beck, P.S., Wang, T.J., Skidmore, A.K., Song, Y.L., Gong, H.S., Prins, H.H., 2010. Effects of plant phenology and solar radiation on seasonal movement of golden takin in the Qinling Mountains, China. J. Mammal. 91 (1), 92–100.

Further reading

SAS 12.3 System Documentation. SAS Products: User's Guide FASTCLUS Procedure.

Title 25 of the Code of Federal Regulations (CFR), Part 163.3 (b) (1). Available online at: < http://www.ecfr.gov/cgi-bin/text-idx?SID&node=pt25.1.163&rgn=div5 > (last accessed on Feb. 26, 2016).

USDA Forest Service. Coincidence Boundary Forest Service/Indian Lands in Arizona & New Mexico. Available online at: < http://www.fs.usda.gov/Internet/FSE_MEDIA/fsbdev3_020582.gif> (last accessed on Feb. 26, 2016).