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Delineating a managed fire regime and exploring its relationship to the natural fire regime in East Central Florida, USA: A remote sensing and GIS approach

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ABSTRACT

A managed fire regime on John F. Kennedy Space Center, Florida and surrounding federal properties was mapped using time series satellite imagery and GIS techniques. Our goals were to: (1) determine if an image processing technique designed for individual fire scar mapping could be applied to an image time series for mapping a managed fire regime in a rapid re-growth pyrogenic system; (2) develop a method for labeling mapped fire scar confidence knowing a formal accuracy analysis was not possible; and (3) compare results of the managed fire regime with regional information on natural fire regimes to look for similarities/differences that might help optimize management for persistence of native fire-dependent species. We found that the area burned by managed fire peaked when the drought index was low and was reduced when the drought index was high. This contrasts with the expectations regarding the natural fire regime of this region. With altered natural fire regimes and fire-dependent species declining in many pyrogenic ecosystems, it is important to manage fire for the survival of fire-adapted native species. The remote sensing and GIS techniques presented are effective for delineating and monitoring managed fire regimes in shrub systems that grow rapidly and may be appropriate for other fire-dependent systems world wide.

1. Introduction

The behavior of many individual fire events summed over years is collectively known as a fire regime and is defined by fire type, intensity/severity, size, return interval, seasonality, and spatial pattern (Christensen, 1985; Agee, 1993). Natural fire regimes have been altered by humans and no longer maintain many fire-dependent ecosystems around the globe. Human influences such as fuel removal, fuel fragmentation, fire suppression, and increased fire frequencies are among the principle factors altering natural fire regimes (Leach and Givnish, 1996; Cochrane, 2003; Duncan and Schmalzer, 2004; Heinlein et al., 2005). Many ecosystems are suffering from altered fire regimes (Olson and Platt, 1995; Allen et al., 2002; Odion et al., 2004), and as a result have allowed fire sensitive exotic species to thrive (Brooks et al., 2004). Fire management is now necessary as a synthetic forcing to approximate natural fire regimes (Noss and Cooperrider, 1994).

The ability of land managers to mimic natural fire regimes may be essential to sustain diverse assemblages of native fire-adapted species. Monitoring of managed fire regimes is thus important to evaluate management goals, provide information necessary for adaptive management, and compare to natural fire regimes. Remote sensing techniques are suitable for fire monitoring in many open or crowning fire-maintained systems (Minnich, 1983; Salvador et al., 2000; Russell-Smith et al., 2003; Bowman et al., 2004; Fisher et al., 2006). Relatively new satellite fire monitoring tools such as MODIS Fire, TRMM VIRS, and ATSR-2 are superb for recent (post-1995) fire history mapping at coarse scales (Csiszar et al., 2005; Bradley and Millington, 2006). For longer fire histories, especially when fine detail pattern information is necessary, mapping fire scars from a time series of high resolution imagery is preferred (Fuller, 2000; Bowman et al., 2003).

A managed fire regime has been in place on Kennedy Space Center (KSC)/Merritt Island National Wildlife Refuge (MINWR) since 1981. This managed fire regime includes prescribed and natural lightning fires, all of which are ultimately controlled. Text records have been maintained documenting the cause, size, and general management unit location of every known fire on these properties. Detailed fire boundary information is missing from these records and is necessary to aid effective habitat management

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of native fire-maintained species. This pyrogenic system is home to many fire-dependent native species that have been in decline in the southeastern United States due to habitat destruction and fire regime alteration. One such species is the Florida Scrub-Jay (*Aphelocoma coerulescens* Bosc.), which is dependent on fine scale burn patterns for optimum demographic performance (Breininger et al., 2006).

In this paper our goal was to answer the following three questions: (1) Could an image processing technique developed for mapping individual fire scars (Shao and Duncan, 2007) be applied to an image time series to map/describe a managed fire regime, within a rapid re-growth pyrogenic system on KSC/MINWR and surrounding federal properties of east central Florida, USA? (2) Could we develop a method for determining the level of confidence with which each fire scar was mapped, because the historic nature of this fire regime reconstruction would inhibit our ability to conduct a formal accuracy assessment of our maps? (3) Could we compare the results of this managed fire regime with expected spatio-temporal patterns of the natural fire regime from other published studies to assess differences and help improve fire management benefiting native fire-dependent species?

2. Background/study site

The United States federal government began acquiring land in the 1950s on Cape Canaveral and in 1962 on north Merritt Island, along the east coast of central Florida. KSC covers 57,000 ha of land, which is primarily managed by the U.S. Fish and Wildlife Service as the Merritt Island National Wildlife Refuge with a smaller portion managed by the National Park Service as the Canaveral National Seashore (CNS). Cape Canaveral Air Force Station (CCAFS) is 6475 ha and occupies the Cape Canaveral barrier island (Fig. 1). After the federal government acquired the land, fires were suppressed until 1981, at which point catastrophic wildfires (due to fuel build up) became a safety and operations problem on KSC/MINWR. The first fire management plan for KSC/MINWR was developed in 1981 to reduce dangerous fuel levels and prevent future fuel build up (Lee et al., 1981; Adrian et al., 1983). The realization that natural communities were becoming degraded and concern for wildlife species led to fire being used as a tool for restoring and maintaining natural communities on KSC/MINWR (Schmalzer et al., 1994).

When referring to these properties collectively we will use the first letter from each location and shorten the name from KSC/MINWR/CNS/CCAFS to KMCC. KMCC occupies a barrier island complex covered with a diverse assemblage of fire-adapted terrestrial vegetative communities. Upland xeric sites are dominated by oak scrub vegetation (*Quercus* spp.), while mesic sites are dominated by flatwoods (e.g., saw palmetto (*Serenoa repens* (W. Bartram) Small), staggebrush (*Lyonia* Nutt. spp.), holly (*Ilex* L. sp.), and an overstory of slash pine (*Pinus elliotii* Engelm.) (Schmalzer and Hinkle, 1992a,b). Because the landscape is comprised of relict dunes forming ridge-swale topography, there are interleaving swale marshes and hammocks on hydric soils between the xeric ridges. The swales are dominated by cordgrass (*Spartina bakeri* Merr.) and bluestem (*Andropogon* L. spp.), while the hardwood hammocks are dominated by live oak (*Quercus virginiana* Mill.) and laurel oak (*Quercus laurifolia* Michx.) and have a structure that is much less flammable than surrounding communities. Coastal strand occurs just inland of the coastal dunes and is a shrub community with saw palmetto, sea grape (*Coccoloba uvifera* L.), wax myrtle (*Myrica cerifera* L.) being dominant (Schmalzer et al., 1999). An extensive network of industrial infrastructure and facilities supporting launch operations are present.

Many of KMCC's species of special concern are directly dependent on habitat structures maintained by fire. This is the case for the Florida Scrub-Jay; it is listed as a federally threatened species and is considered an indicator of suitable habitat conditions for many other species. Suitable Scrub-Jay habitat includes areas with sandy openings, sufficient scrub oak cover, little or no tree cover, and shrub heights of 1–2 m (Woolfenden and Fitzpatrick, 1984; Breininger et al., 1995; Duncan et al., 1999). KMCC is one of the three remaining population cores for the Florida Scrub-Jay (Stith et al., 1996).

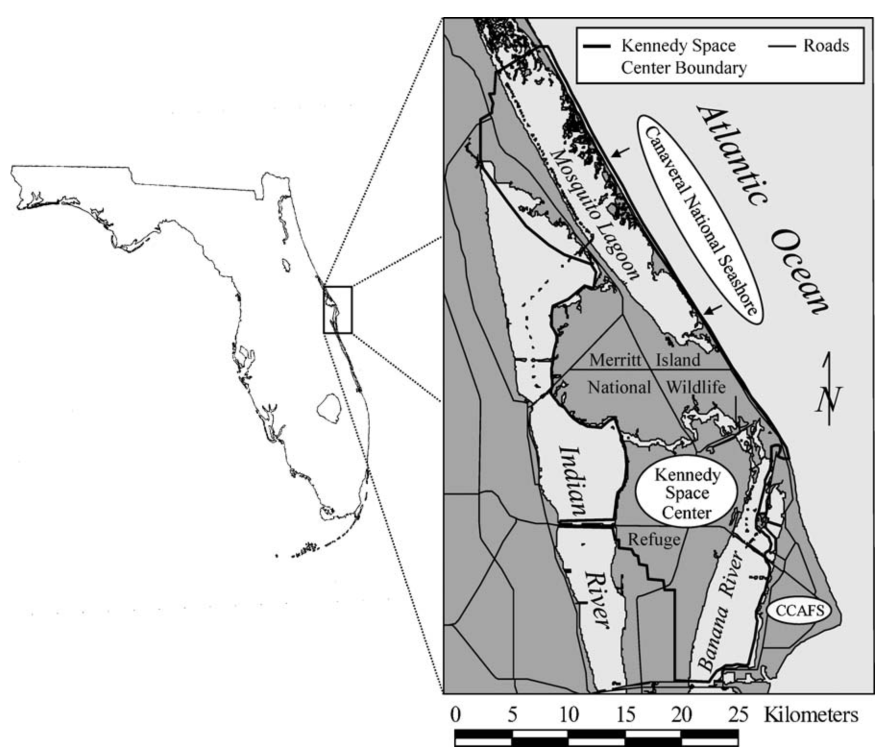

Fig. 1. The geographic locations of Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station.

On these federal properties, arson fire is generally not part of the contemporary fire regime. This is because much of the area within this study is inside secured boundaries restricting human ignitions to prescribed fires only. In contrast, arson and escaped incendiary fires are now a major component of many contemporary fire regimes in the southeastern United States (Genton et al., 2006). For this reason, the federal properties in this study are ideal for studying a managed fire regime because it is not confounded by unplanned anthropogenic wildfire.

3. Methods

3.1. Burn scar classification

A time series of multispectral satellite imagery was used to map fire scars (burned areas identifiable on imagery by bare ground and dark charcoal/ash appearance). The image data consists of multiple bands collected in the visible and infrared spectral wavelengths that are used for classification and discriminative purposes. Two images a year were used to maximize the number of fire scars mapped, due to the rapid vegetation growth rates following disturbance on KMCC (Schmalzer and Hinkle, 1992b; Schmalzer, 2003). A total of 40 satellite scenes (pre-processed with geometric and radiometric correction) were used dating from 1984 to 2005, 39 were Landsat Thematic Mapper (TM) images and 1 was a SPOT image needed to fill a gap in TM availability (Table 1). Using the first image from 1984, we were able to map some of the fires that occurred in 1983. Because there was only one SPOT image we employed a conventional unsupervised classification (Jensen, 2005) on the original bands and used the MINWR fire records to select the best classified image. The image processing technique that was used to classify fire scars in each individual Landsat TM scene was more rigorous and followed Shao and Duncan (2007). This source should be consulted for details on the technique, including accuracy assessment information. This classification routine consists of the following general steps:

(1) Each satellite scene was rectified to State Plane NAD83 Meters to be compatible with existing spatial data and so it could be clipped to the geographic boundaries of the federal properties (see Shao and Duncan, 2007 for complete discussion of the influence of geographic area on classification results).

(2) A non-parametric separation index (SI) was used to select the best bands for classifying burned areas. The ideal bands have burned and unburned areas separated by their spectral signature, making them unique and easy to classify, hence the separation index. For each band, histograms of pixel spectral values were computed for burned and unburned areas as derived by visual interpretation and MINWR fire records. Areas were derived by knowing the image pixel size (e.g., Landsat TM is 30 m) and frequency from the histograms. To avoid bias caused by the burned or unburned cover type with larger area, the overlap area was divided by the area of the smaller cover type. SI is calculated as follows:

$$\mathrm{SI}_{i,j} = 1 - \frac{A_{i,j}}{\mathrm{Min}(A_i, A_j)} \quad (1)$$

where $\mathrm{SI}_{i,j}$ is separation index between cover types i and j ($0 \leq \mathrm{SI}_{i,j} \leq 1$), $A_{i,j}$ is the overlap area between cover types i and j, A_i or A_j is area for cover type i or j, and Min represents the minimum function (smaller number between A_i and A_j).

The higher the $\mathrm{SI}_{i,j}$ value, the more discriminative power the band has to separate the two cover types. All the bands with an $\mathrm{SI}_{i,j}$ value greater than 0.1 were accepted for classification. Bands with SI values > 0.5 were designated the most suitable bands. One TM band (TM4—near infrared), and three transformed bands (Normalized Difference Vegetation Index, Principal Component 4, and Tasseled Cap 2) (Jensen, 2005) were collectively used for classifying burned from unburned areas.

(3) The unsupervised classification algorithm ISODATA was employed because it is a consistent and repeatable classification method suitable for use on an image time series. The number of spectral classes was 20, the number of iterations was 20, and the convergence threshold was 0.99 for all the classifications with different band combinations. The 20 spectral classes were then manually recoded into two information classes, burned and unburned, to form the classified fire-scar maps.

Table 1
Multispectral satellite imagery used to map fires on Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station.

Image date (YYYY, MM, DD)	Image type	Satellite #	Image date (YYYY, MM, DD)	Image type	Satellite #
1984, 05, 14	TM	5	1995, 12, 07	TM	5
1984, 11, 06	TM	5	1996, 03, 12	TM	5
1985, 01, 09	TM	5	1996, 12, 09	TM	5
1985, 05, 17	TM	5	1997, 01, 26	TM	5
1986, 04, 02	TM	5	1997, 06, 19	TM	5
1986, 08, 24	TM	5	1998, 03, 02	TM	5
1987, 04, 21	TM	5	1998, 07, 24	TM	5
1987, 12, 01	TM	5	1998, 12, 31	TM	5
1988, 04, 07	TM	5	1999, 01, 16	TM	5
1988, 12, 19	TM	5	1999, 09, 05	TM	5
1989, 04, 26	TM	5	2000, 01, 11	TM	7
1989, 11, 20	TM	5	2000, 04, 05	SPOT	4
1990, 10, 06	TM	5	2001, 04, 01	TM	5
1991, 08, 06	TM	5	2001, 08, 25	TM	7
1992, 05, 04	TM	5	2002, 02, 17	TM	5
1993, 01, 31	TM	5	2002, 04, 22	TM	5
1993, 07, 10	TM	5	2003, 01, 19	TM	7
1994, 05, 26	TM	5	2003, 05, 27	TM	7
1994, 11, 02	TM	5	2004, 05, 05	TM	5
1995, 03, 26	TM	5	2005, 03, 05	TM	5

Landsat Thematic Mapper (TM) scenes are path 16, row 40 with less than 10% cloud cover and pre-processed to level 1T (geometric and radiometric correction). A single Satellite Pour l'Observation de la Terre (SPOT) scene was used to fill a gap in landsat coverage with the K/J designation 536/280 and pre-processed to level 2A (geometric and radiometric correction).

(4) Following each classification, the fire-scar maps were masked with a GIS data layer of the burned fire management units (FMUs). This masking process, called post-classification cleaning, took advantage of the MINWR fire records and masked out any unburned FMUs. This step removed commission errors outside burned FMUs and helped produce a high quality fire-scar map.

3.2. GIS database

After the fire scar maps were visually inspected and identified problems were rectified, the final thematic maps were converted from ERDAS Imagine (Leica Geosystems, 2008) into ArcGIS GRID format (ESRI, 2008), and then to a vector format. Attribute information such as burn date, FMU, type of burn (prescribed vs. natural), and age (time since last burn), were added to the fire scar maps. Because MINWR maintained a database containing both natural and prescribed fires on KMCC since 1977, it was possible to assess and label fire boundary confidence by comparing visual evidence of burn scars on the satellite images and the classified burn scars with the MINWR fire records. If there was agreement between all forms of evidence, the burn scar was labeled with a high confidence value, and if not, the burn scar was labeled with a lower value of confidence. The confidence value (CV) ranged from 1 to 4 and was also added to the fire scar maps (Fig. 2). A CV of 1 indicates low confidence in fire scar boundaries with a value of 3 or 4 indicating high confidence in mapped fire boundaries. This is a similar application of classifying landcover confidence (Liu et al., 2004), but modified for application to mapping fire scars. Results are presented with confidence level information, allowing the selection of mapped features based on the confidence in which the fire scars were mapped. The confidence values are important because they provide a means for documenting mapped feature quality despite the inability to conduct a formal accuracy analysis due to the historic nature of this study.

The time difference between each fire date and the date of the closest image acquired after that fire (used to map that fire scar) was recorded in months and called the delta burn date. This was done for each recorded fire using the MINWR fire database and combined with the confidence item information. We wanted to know how fast the rapidly growing vegetation in this region takes to obscure fire scars, indicating how many images are required per year to map high quality (high confidence) fire scar boundaries. Insight into this question could be gained by exploring how the mapped confidence decreased with increased time since burn (delta burn date). In addition, each fire scar was categorized into one of three dominant landcover types (wetland, flatwoods, or scrub) to determine how re-growth rates of each landcover type influences the ability to map high quality fire scar boundaries.

Landscape age, landscape fire frequency, and dominant burn season maps were created in the GIS. An Arc Macro Language program was written to combine all of the individual fire boundary maps into a single GIS data file. Burn date attribute information was exported to Microsoft Access (Microsoft 2008) for each burn polygon (record) in the database. The season of burn was tallied and then the attribute information was appended back to the GIS database where a map showing the dominant burn season (most frequently burned season) for each area was produced. Seasons were defined so that the months of December, January, and February comprised Winter, the months of March, April, and May comprised Spring, the months of June, July, and August comprised Summer, and the months of September, October, and November comprised Fall.

To analyze the relationship between annual fire area and drought variation, burn area by year, month, season, and drought data were organized in Microsoft Excel (Microsoft 2008). Statistical

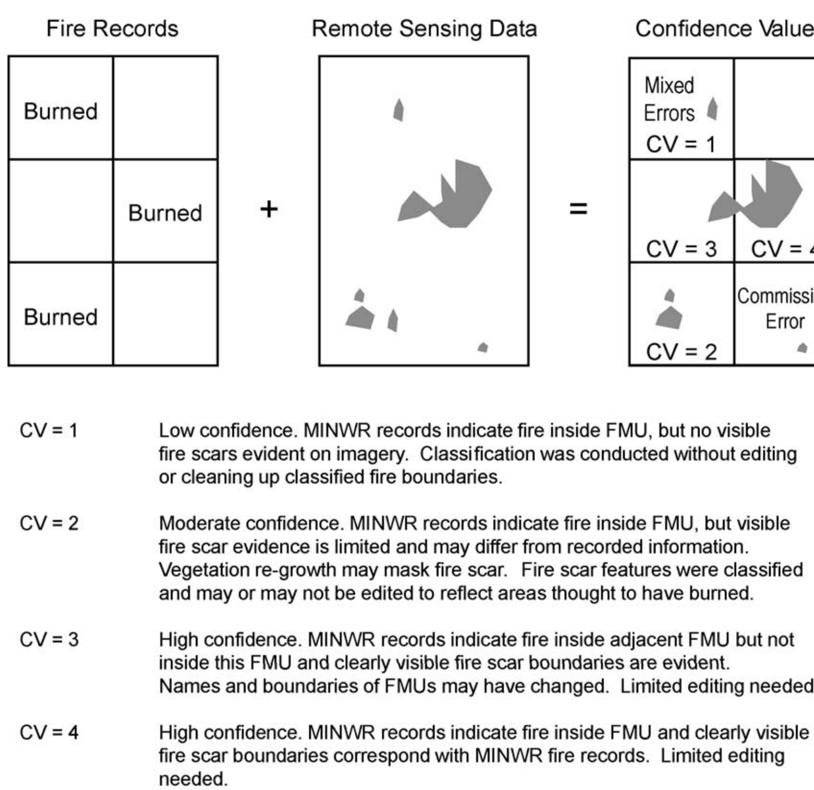

Fig. 2. The process of determining and labeling fire boundary confidence values (CV). The diagram on the left symbolizes the fire records kept by Merritt Island National Wildlife Refuge (MINWR). The diagram in the middle represents fire scars mapped from satellite imagery. The diagram on the right shows how the information is used to label mapped confidence values.

Table 2
Delta burn date statistics for fire scars mapped between 1983 and 2005 on KMCC, Florida.

Cover type	Mean	Median	Minimum	Maximum
(a)				
Wetlands	3.0	2.0	1	11
Flatwoods	3.7	3.0	1	10
Scrub	4.0	3.0	1	10
(b)				
Wetlands	2.3	2.0	1	6
Flatwoods	3.9	4.0	1	10
Scrub	4.0	3.0	1	10

Delta burn date is the time difference in months between a fire and the next image in time series (after that fire) used to map the burn scar. Confidence values of (a) 1–4 and (b) 3–4.

analysis was performed in the statistical software package, SPSS (SPSS Version 12.0 2008). The drought information used was the cumulative severity index (CSI) or Keetch–Byram Drought Index (Keetch and Byram, 1988). These data were recorded by MINWR personnel for 1995–2004, excluding 1996. The CSI is a cumulative algorithm for estimating fire potential from meteorological inputs such as daily maximum temperature, daily total precipitation and mean annual precipitation. The CSI daily values were averaged by month for statistical analysis.

4. Results

4.1. Mapped confidence and fire boundary degradation

The delta burn date values were the smallest for wetlands and largest for scrub landcover types (Table 2). This trend was the same for the delta burn dates with CVs of 3 and 4. There were 24 fire scars labeled with a confidence greater than 3 and a delta burn date period greater than 6 months (these were the largest delta burn dates and had the highest confidence values). All except one of these fires were growing season fires indicating that growing season fire scars may have a longer residency time on the landscape making them easier to map using remote sensing. The growing season varies for each species but the core growing season for dominants in this system is from April through early October.

4.2. Seasonality/area/size managed fire regime elements

A total of 54,175 ha were mapped as burned between 1983 and 2005. Of that total, 48,601 ha were mapped as burned with a CV > 1. Only 10% of the mapped burn area had a CV = 1. The amount of area burned peaked in 2003 for all confidence values and peaked in 1997 for CV > 1, with reduced amounts of burned area in 1999 and 1990, respectively (Fig. 3). Area burned peaked in the month of November with the lowest amount in October (total can be found by taking the average multiplied by number of years = 21) (Fig. 4). Annual variability in monthly area burned was generally low, with variability being greatest in November, the month with the highest average and total burn area. Area burned reached a maximum in the winter season and a minimum in the spring for all CVs and a minimum in the summer for CV > 1 (Fig. 5). Annual variability in season burned is very low with uniformly small standard error bars.

The CSI values for each year were highly variable (Fig. 6, A–I). The monthly mean for all years indicated that the CSI peaked in May and reached a low in October (Fig. 6, J). April is typically the start of the spring dry period (Mailander, 1990) so we investigated the relationship between April drought index and area burned. Total area burned and CSI for April of each year (1995,1997–2004) were normally distributed (Shapiro-Wilk test, $P = 0.598$, $P = 0.719$) and negatively correlated ($r = -0.693$, $P < 0.038$).

Areal extents for single fires had a mean of 198 ha, a median of 112 ha, a minimum of 0.73 ha, and a maximum of 1324 ha for all CVs. For CVs > 1, the mean was 209 ha, the median was 126 ha, the minimum was 1.26 ha, and the maximum was the same at 1324 ha.

4.3. Frequency/return interval managed fire regime element

The mean fire frequency was 12 fires per year (274 total fires/23 years), the minimum was four fires per year, and the maximum was 24 fires per year for all confidence values. For CVs > 1, the mean fire frequency was 10 per year (233 total fires/23 years), the

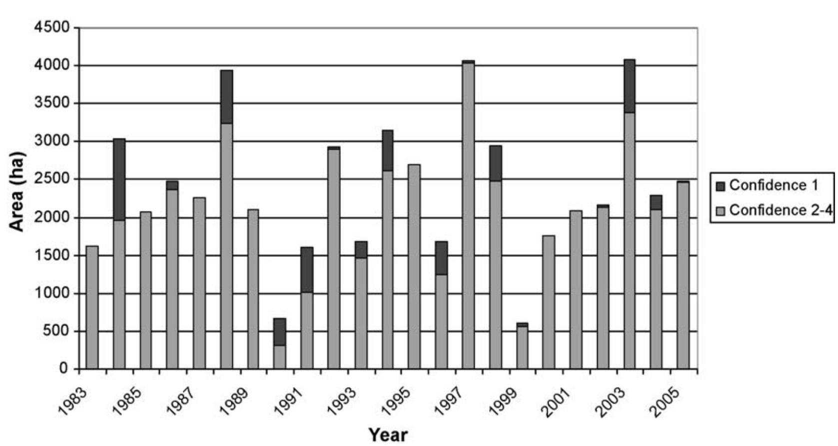

Fig. 3. Mapped burn scar area by year for Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station. Areas were summarized by confidence values 1 and 2 through 4.

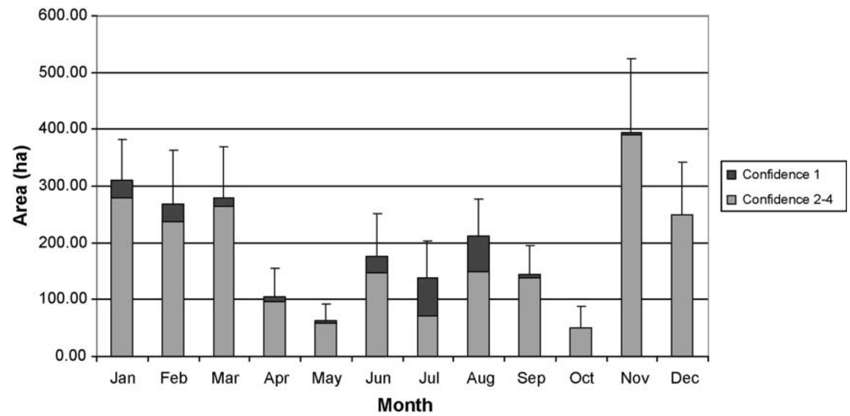

Fig. 4. Annual average burn area by month for Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station. Winter was comprised of December, January, and February; Spring was March, April, May; Summer was June, July, August; and Fall was September, October, November areas were summarized by confidence values 1 and 2 through 4 for the period of 1984–2004. Error bars represent standard error for confidence values 1 through 4.

minimum fire frequency was one per year, and the maximum was 19 per year. Fire frequency peaked in 1997 and the low was in 1990 for years with a complete burn record (Fig. 7).

The fire cycle is defined as the amount of time needed to burn an area equal to the study site, in this case, 27,500 ha (area of open water excluded). The fire cycle (fire rotation) at KSC/MINWR, excluding CCAFS and CNS, was 12 years for all CVs and 13 years for CVs > 1. Because the fire cycle is measured in years, the initial year (1983) of study was excluded from the calculation, because the available satellite imagery did not allow mapping of all fires for that year. The calculation started with 1984 and each annual burn total was added until the flammable area of the study site (27,500 ha) was reached, the number of years added became the fire cycle. The fire cycle was very similar to the return interval of 11.5 years for all confidence values and 13 years for CVs > 1. The return interval is calculated by dividing the upland flammable area (27,500 ha) by the average area burned each year (2393 ha). The same calculation was followed for CVs > 1 (2120 ha).

4.4. Spatial pattern managed fire regime element

The landscape mosaic maps cover 21,528 ha for all CVs and 20,659 ha for CVs > 1. We present the confidence maps 2 through 4 in this paper because they represent areas that we are certain burned. Recent burn categories are prevalent on the age class mosaic map and tend to occur in large blocky polygons due to the burns being conducted in management units with linear boundaries (Fig. 8). The age mosaic map has a mean polygon size of 2.65 ha, a minimum of 0.002 ha, and a maximum of 887 ha. The majority of the burned area is in the young age classes (Fig. 8, histogram inset). The age mosaic map also makes it evident that fire has been excluded from much of CNS and the majority of CCAFS.

Fire frequency was manifested in much finer scale patterns than the age mosaic map and there is a single fire frequency hot spot that burned seven or eight times (Fig. 9). The frequency mosaic map is a combination of the 233 fires that occurred between 1983 and 2005 with CVs > 1. This map has a mean polygon size 0.90 ha, a minimum of 0.002 ha, and a maximum of 222 ha. The majority of area on this landscape belongs to the low frequency categories (Fig. 9, histogram inset). Winter season burns were prominent (Fig. 10). The multiple burn season category covered the largest area, with the smallest being the spring season (Fig. 10, histogram inset).

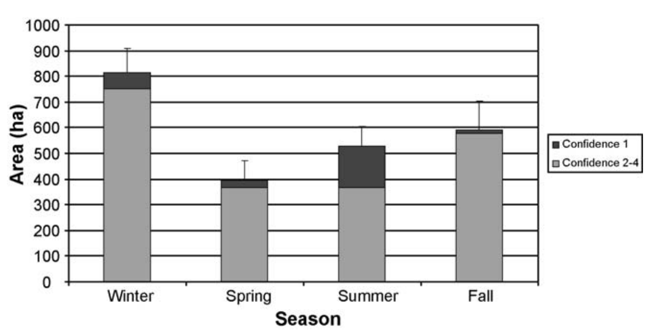

Fig. 5. Annual average burn area by season for Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station. Winter was comprised of December, January, and February; Spring was March, April, May; Summer was June, July, August; and Fall was September, October, November. Areas were summarized by confidence values 1 and 2 through 4 for the period of 1984–2004. Error bars represent standard error for confidence values 1 through 4.

5. Discussion

5.1. Mapped confidence and fire boundary degradation

Due to the rapid vegetation growth rates, we did not know how many images would be needed annually to guarantee that we could map every fire that occurred in our study. Experience dictated that one a year would not be suitable to map accurate boundaries so we acquired two (one spring and one fall) each year. Because the time gap between images was not always exactly 6 months apart (some were longer), it allowed us to explore the limits of our classification technique to delineate high confidence fire scar boundaries after time intervals exceeding 6 months following fire. The confidence values helped provide guidance on mapping quality (high confidence) fire scar boundaries and their degradation with time since burn. We tested the outer limits of detectability, for example, using our first image in the series, we tried to map fires as far back into 1983 as possible and lost the ability to detect any fire scars occurring eleven months prior to the date of image acquisition. Getting the optimum number of images in series is important so that an ideal balance can be created between reducing imagery costs, minimizing classification effort, and maximizing the quality of fire regime reconstruction. If our primary objective was to map fire scars in marshes, than we would need a higher number of annual images, likely a minimum of three. We conclude that for general mapping of fire scars, two images a year spaced about 6 months apart, acquired in the spring and fall is

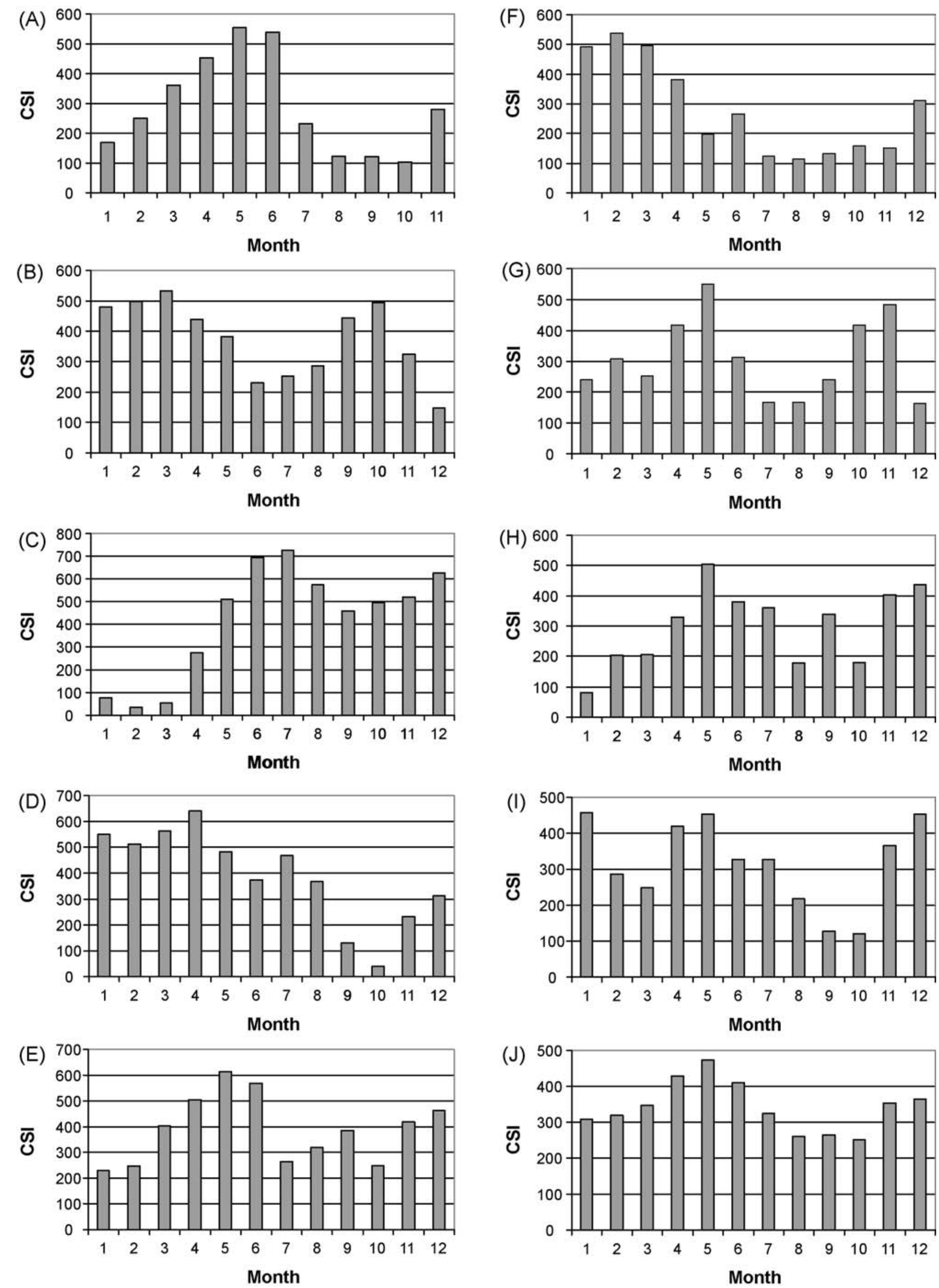

Fig. 6. Cumulative Severity Index (CSI) drought data presented by monthly average. Drought index for (A) 1995, (B) 1997, (C) 1998, (D) 1999, (E) 2000, (F) 2001, (G) 2002, (H) 2003, (I) 2004, and (J) monthly average for all years.

reasonable in relation to the tradeoffs discussed above. The number of images may be dependent on the time of year also, for example, to map marsh fire scars it might be necessary to have images every 2 months during the growing season but further apart during other times of the year. More study may be required to truly optimize the number of images in this system or any other.

Using the confidence information, we determined that the most persistent fire scars were left by growing season fires. These fires had the largest delta burn dates and this may signify that growing season fires take a longer time to re-establish vegetative cover following disturbance. This makes sense as the large flush of leaves occur at the beginning of the growing season (generally late March) prior to most of these fires and then the plants are dormant in fall/winter.

5.2. Comparison of managed and natural fire regimes

5.2.1. Seasonality/area/size fire regime elements

Current theory derived from empirical evidence holds that most burning under the natural fire regime occurred during the early growing season (April–June) in this region (Slocum et al., 2003; Platt et al., 2006). Large fires would occur at this time of year because fuels were dry, ground water levels were low, and lightning frequencies were relatively high simultaneously. The April–June period is the maximum in the mean rain-free interval and minimum in mean ground water level for this region (Mailander, 1990; Schmalzer and Hinkle, 1990; Platt et al., 2006). Limited convective storm activity begins during this time, providing lightning activity but not yet depositing large quantities

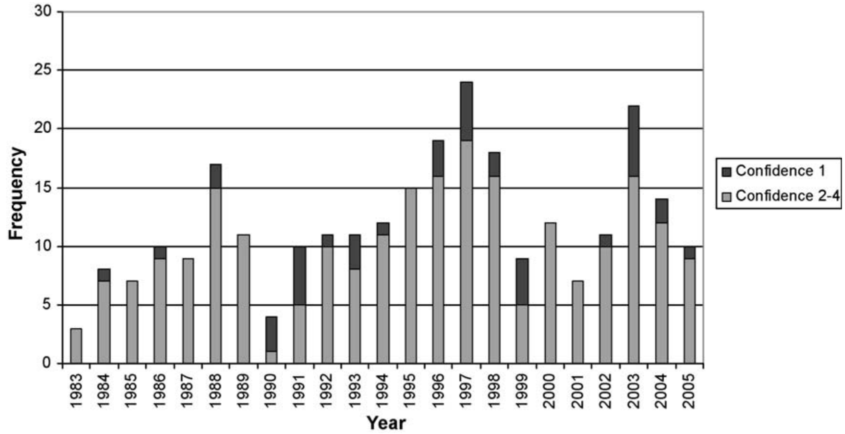

Fig. 7. Mapped burn frequency by year for Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station. Frequencies were summarized by confidence values 1 and 2 through 4.

of rainfall. These factors created ideal conditions for large, extreme fire events during late spring/early summer in this region. This was particularly true during La Niña periods that magnified dry early growing season periods (Harrison and Meindl, 2001; Beckage et al., 2005).

The largest fire recorded in this present study was 1324 ha during the La Niña period in June of 1998 ignited by lightning. This fire would have burned a much larger area if it were not controlled. This fire burned across many fire lines and consumed nearly all fuels in its path before it was brought under control (Breininger et al., 2002). Fire modeling shows that large, extensive fires likely occurred across this landscape before fragmentation was prevalent (Duncan and Schmalzer, 2004).

The negative correlation of April CSI and total acreage burned indicates that under the managed fire regime the opposite of the natural system is occurring with the largest acreages burning when April CSI values are low. April is typically the first month of the dry season, and if April is extremely dry, this will limit prescribed burning until appreciable rain occurs. During periods of drought (high CSI), area burned declines and during wet periods (low CSI) area burned increases. Under the managed fire regime, November is also the month of maximum area burned annually, and winter is the season that most area is burned.

The influence of burn season has been investigated in some of the fire adapted communities of the southeast and these results have implications for survival of many fire-dependent species in this ecosystem (Hiers et al., 2000; Liu et al., 2005; Brewer, 2006). Generally, burn season has a larger influence on the abundance of seeding species than resprouting species in this region. Burn season influences flowering and hence seed generation of wiregrass (*Aristida stricta* Michx.), an important foundational species supporting fire in the understory of longleaf pine and flatwoods communities (Outcalt, 1994; Mulligan and Kirkman, 2002). Burn season was found to have little effect on post-fire recovery of resprouting Florida scrub species in the flatwoods communities on KSC/MINWR (Foster and Schmalzer, 2003).

The influence of burn season is clearly important depending on the ecosystem and the species within them. Fire is not the only seasonal natural phenomenon influencing ecosystem structure. Fires followed by flooding produce unfavorable conditions for pine and palm establishment (Platt et al., 2006). Fire intensity is also an important factor that influences the pattern of shrub abundance (Thaxton and Platt, 2006). We mapped fire presence/absence in this study, but it may be possible to map fire severity from Landsat TM data as it has been achieved in other ecosystems (Patterson and Yool, 1998; van Wagtendonk et al., 2004; Duffy et al., 2007; Stow et al., 2007; Wimberly and Reilly, 2007).

The annual area burned and fire frequency (Figs. 3 and 7) show a cyclical nature by rising and falling within an 8–10 year pattern. When El Niño and southern oscillation (ENSO) events are superimposed on these it appears that there may be a relationship between them (Fig. 11). Area burned and fire frequencies from managed fires tended to increase during or immediately after El Niño events and declined during or immediately after La Niña events. The variability in lag time between the onset of sea surface temperature changes, climatic response and fire management action made determining the specific relationship between ENSO events and area burned difficult for the relatively short duration of this study.

The combination of drought and lightning determines the seasonality of the natural fire regime in this region (Beckage et al., 2005; Slocum et al., 2007). The variability of the CSI data suggests that the availability of a natural ignition source (lightning) is the timing mechanism and the key to the seasonality of the natural fire regime. The highest mean CSI is reached in May and the lowest value is reached in October. This result backs the findings in the literature. The variability found in the individual years however, suggests that because drought values can be high during just about any month within any given year, the critical factor is lightning availability, creating a coincidence of both. The CSI drought index considers rainfall, temperature, and ultimately soil moisture (Keetch and Byram, 1988), so when CSI values approach 600 it is very likely that a fire will ignite given an ignition source. The CSI data for 1998 has both the lowest and highest CSI values of any year in this study. This year was known for its rapid turn around from El Niño to La Niña and the outbreak of wildfires during the summer of this year due to the drought and "dry" lightning strikes (Pye et al., 2002).

5.2.2. Frequency/return interval fire regime element

The fire return interval and fire cycle indicate relatively frequent managed fire. Estimated fire return interval ranges in Florida for mesic flatwoods are from 1 to 8 years and 8–25 years for scrubby flatwoods (FNAI and DNR, 1990). These communities are dominant in our study area, supporting our fire cycle and return interval values. Fire return interval information can be used to compare the difference between and within systems for both natural and contemporary fire regimes (Odion and Hanson, 2008), but it is important to get dependable return interval values into the literature to facilitate comparison.

5.2.3. Spatial pattern fire regime element

Burn pattern is also important and is influenced by season (Slocum et al., 2007). Fuel connectivity is higher during the early growing season, particularly during La Niña (Beckage et al., 2005)

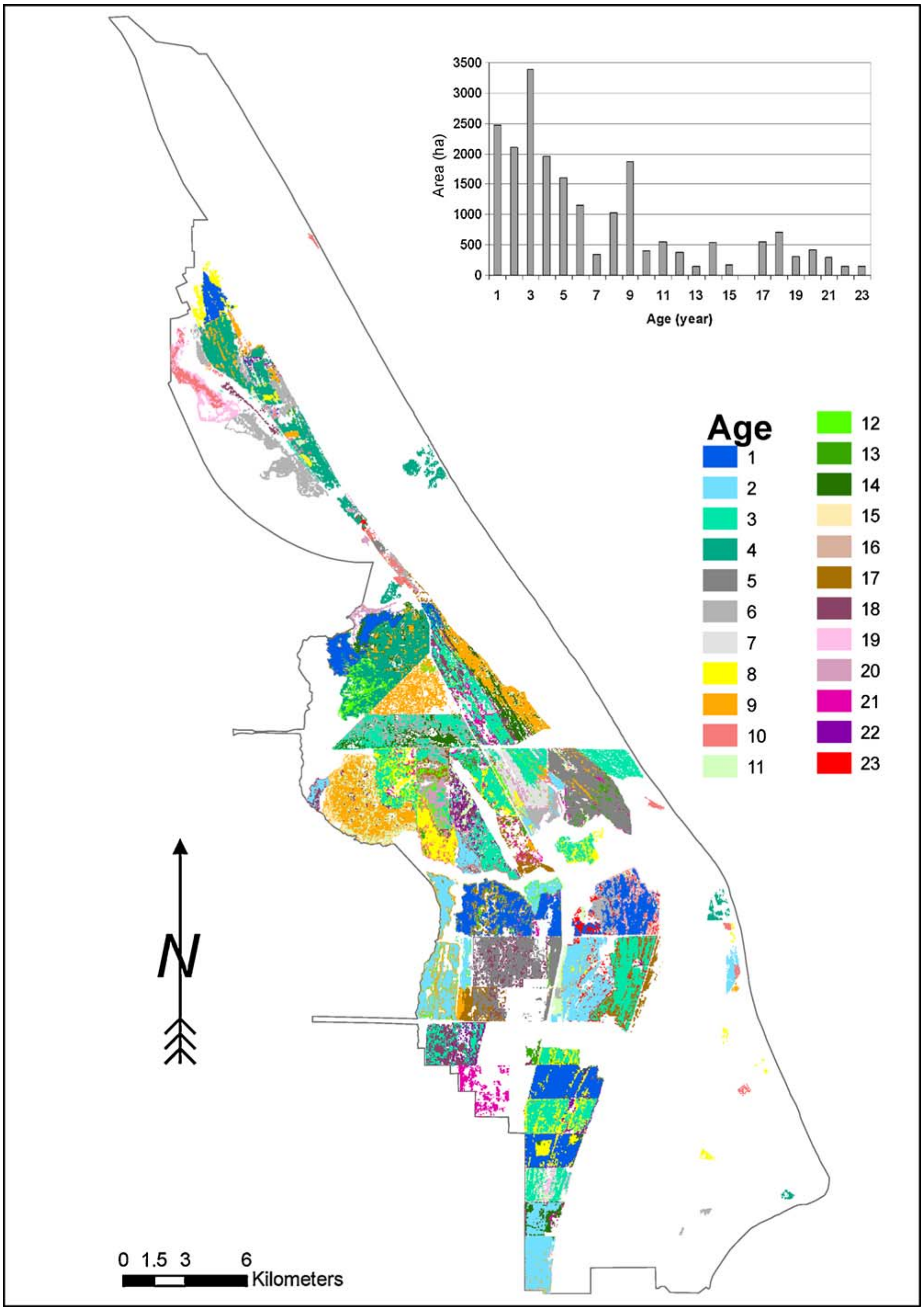

Fig. 8. Landscape age mosaic map and associated area (inset) for Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station. Age is the time since last burn, initialized from 2006, the year the mapping was complete. Areas shown are for confidence values greater than one.

when it is relatively hot and dry, leading to extensive hot fires. Naturally ignited late growing season fires tend to be patchy and small relative to fires during the spring drought. This is the period of highest rainfall, and fuels are generally saturated and do not burn as readily. High hydroperiod marshes are full of water at this time and influence burn pattern in the coastal ridge-swale topography present at KMCC.

The potential exists for a positive feedback cycle to occur between invasive exotic species and an altered fire regime (Vitousek, 1990; Brooks et al., 2004). Once exotics are present, it is possible that they gain an advantage over native species through an altered fire regime. With the decline of native foundational species which historically supported natural fire regimes a negative feedback cycle is created or reinforced (Leach and Givnish, 1996; Outcalt et al., 1999; Schmalzer and Adrian, 2001). Burn season and fire frequency are important elements of any fire regime that may influence which species are successful. The dominant burn season map is useful to look for potential species selection bias that may be introduced by a managed fire regime based on burn season and frequency. This dominant burn season map is most useful when the link between fire frequency, fire season, and species demography are known.

The landscape age map has the majority of its area in the young age classes as new fire scars over burn the old ones (Fig. 8, histogram inset). There is a spike in area that is 9 years old, having not burned since 1997. There are many small areas that have not

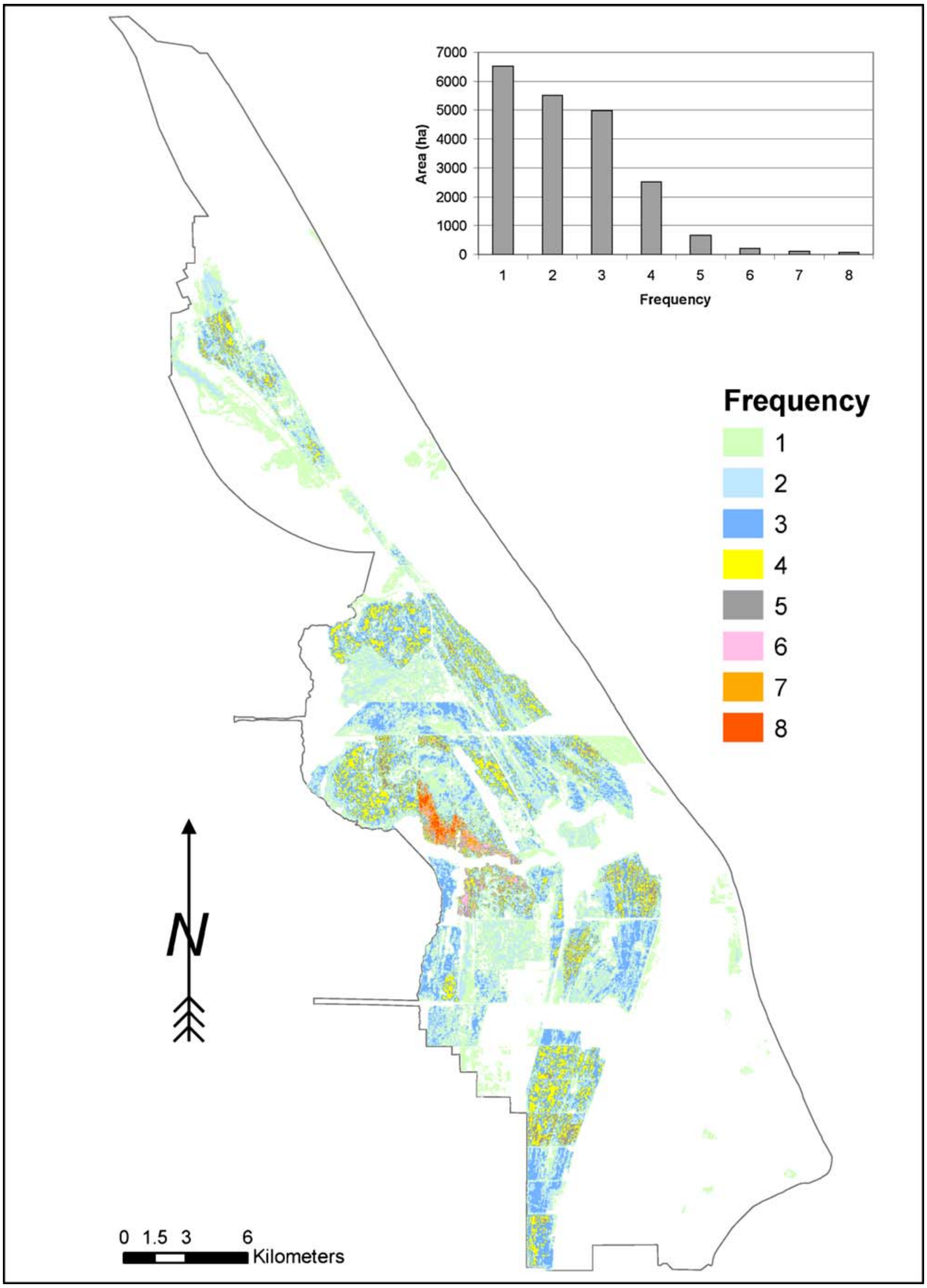

Fig. 9. Fire frequency map and associated area (inset) for Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station. Frequencies derived by overlying all mapped fires with a confidence value greater than one and summing the number of times each area burned.

been burned for longer time periods. These are modern fire refugia and the reason for their resistance to burning should be investigated. Many of these areas may have made a transition to a less flammable fuel/landcover type, which is often the case with a long fire absence (Duncan et al., 1999). The lack of fire in the federal properties surrounding KSC/MINWR makes it appear that they are behind schedule with prescribed burning activities.

The age map shows the latest fire scar over the top of existing burns and reveals a much coarser pattern than the frequency map, shaped by FMU boundaries and fire breaks. The actual physical height structure/stature evident from the fuels/vegetation on the landscape will primarily resemble the pattern of the last fire scar or most recent fire scars. Comparing Fig. 8 histogram inset and Fig. 3, it becomes evident that significant over burning of an area (new fire) generally does not take place for about 7 years. This makes the pattern of each individual fire important (because it will persist for years) when considering native fire-dependent species and their habitat needs. The Florida Scrub-Jay is one such species that is dependent on a particular habitat structure maintained by fire (Breininger and Carter, 2003; Breininger et al., 2006).

5.3. General considerations of mapping a managed fire regime

Managed fire regimes operate under restrictions in addition to the natural controls that governed natural fire. Stringent permitting requirements must be met to receive a burn permit. Primary among them are wind speed, wind direction, relative humidity, drought index, smoke dispersion, and impacts of smoke on roads

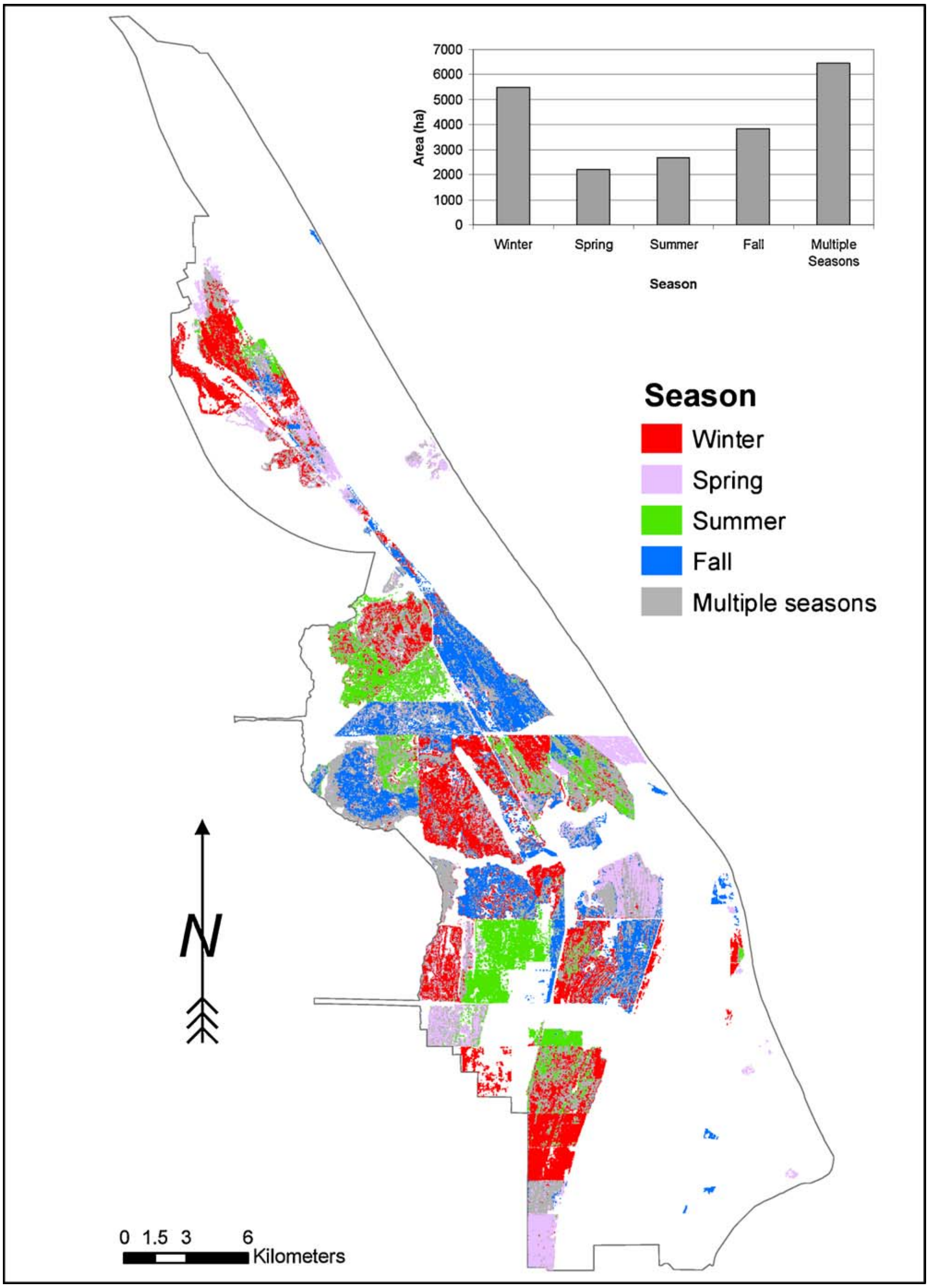

Fig. 10. Dominant burn season map and associated area (inset) for Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station. Areas shown are for confidence values greater than one.

and surrounding cities. In addition, conducting prescribed burns on KMCC has its own set of restrictions (Adrian, 2006). The spaceport has clean room facilities housing expensive payloads being readied for launch into space. Managers in charge of the many spaceport operations often have input into the burn schedule. These restrictions combined with crew and equipment requirements influence the date, location, and size of the prescribed burns that take place.

One of the requirements of controlling fires within a geographic area is the presence of non-flammable fire breaks. This includes roads (dirt or paved) that are just about completely void of fuels or fire lines cleared to mineral soils. The result is that burns often have very geometric shapes. This is very evident particularly in the age and dominant season of burn maps where burn boundaries are made up of straight lines. Natural fire boundaries would likely follow natural ecotone boundaries bordering less flammable fuels such as high hydroperiod marshes, water bodies, or less flammable fuels such as closed canopy hammocks or Florida scrub fuels (Myers, 1990). These fire ecotone interactions would rarely leave straight burn boundaries. Fire refugia may also have been created and maintained by the combination of the predominant wind pattern and these natural fire breaks. Human made fire lines are now largely responsible for the burn patterns found on the landscape and are a contributing factor leading to the low annual burn area variability.

The age classes found on the landscape age map were initialized from the year of 2006. This was the year that the remote sensing of the fire scars was carried out and all of the GIS maps were created.

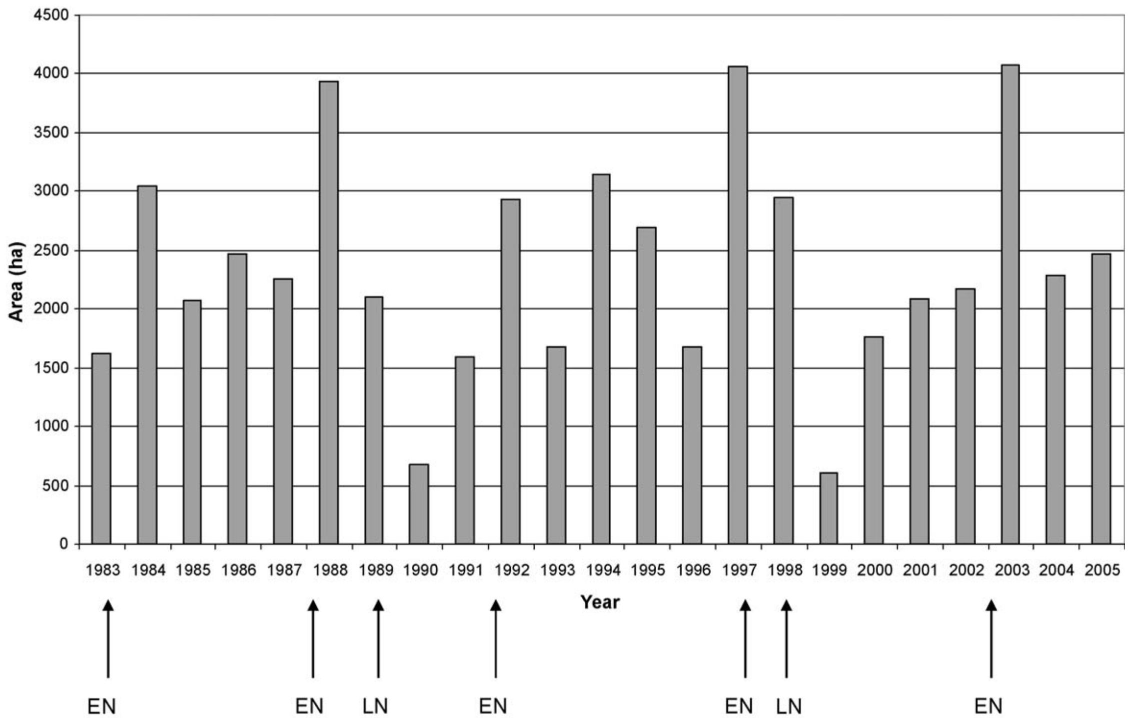

Fig. 11. Burned area by year with El Niño Southern oscillation events superimposed. El Niño events are indicated by EN and La Niña events are indicated by LN. Areas shown are for all confidence values.

These age classes will be updated when recent imagery is available to map the latest fires and update the database. We attempted to map every fire that occurred within the study site boundaries during the study period. Although many small fires did get mapped, some very small fires that occur in the MINWR fire records were not visible on the imagery and did not get mapped.

The classification algorithm performs best in the upland xeric communities (Shao and Duncan, 2007) and has some difficulty in hydric systems, where dark soils and standing water may be confused for burn scars. Safe-guards were instituted to minimize classification errors. Post-classification cleaning or masking was the first safe-guard, the next was to edit out features that consistently did not change with time on previous years imagery (known wetland features) and then lastly, using the confidence values. The confidence value allows the user to remove any fire scar that might have questionable boundaries from consideration. The irony is that the actual number of fires mapped and area mapped as burned may be closer to reality when confidence values of 1 are included. For this reason the normality and correlation statistics were performed on the full data set including all confidence values.

6. Conclusion

This study used remote sensing and GIS techniques to map and describe a managed fire regime on KMCC in east central Florida, USA. Our image processing technique (developed for mapping individual fire scars) was applied to an image time series for successfully mapping and describing a managed fire regime. We developed a system for labeling mapped confidence for each delineated fire scar and demonstrated its utility. This information was used for preferentially selecting fire scars to include or exclude from analysis. It was also used for studying the degradation of fire scar boundaries with time since burn. This information can be used for aiding the selection of a suitable number of images in time series, helping maximize information capture for fire regime mapping projects.

We were able to make comparisons between a managed fire regime and recorded information on natural fire regimes in the southeastern USA. The managed fire regime reacts and functions very differently during wet and dry meteorological periods compared to natural fire regimes of this region. There is an opposing reaction to these meteorological periods, during wet conditions; most area was burned under the managed fire regime and a minimum amount of area would burn under the natural fire regime. The opposite occurred during dry periods; little area burned under the managed fire regime and a maximum would burn under the natural fire regime. April precipitation was an effective predictor for this relationship.

These findings are important because establishing sound fire management practices to mimic the influence of natural fire regimes is increasingly import in the fire-maintained and fire-adapted communities around the world. If fire management is not properly and carefully executed, entire populations of rare species can be at serious risk for survival (Odion and Tyler, 2002). Mimicking natural processes that once effectively maintained diverse assemblages of biodiversity is a very challenging proposition, especially considering imposed anthropogenic influences. The uncertainties surrounding effective fire management make monitoring necessary. Monitoring fire management programs in relation to demography of native species will allow us to learn from successes and failures. Rigorous, scientifically based adaptive management strategies are being developed to help streamline management efforts in complex systems such as the one studied here. Being able to quantify current fire regimes is an important part of improving future fire management to support native fire-dependent species. This paper is a step toward this goal by developing techniques for confidently delineating fire scars in rapid growth scrub systems, allowing the documentation of a managed fire regime. The results here are particularly relevant in east central Florida and the Southeastern U.S., but the techniques may be applicable to any pyrogenic system world wide.

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