Isolating the lightning ignition regime from a contemporary background fire regime in east-central Florida, USA

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Abstract: Anthropogenic influences have altered most fire regimes. Fire management programs often try to mimic natural fire regimes to maintain fuels and sustain native fire-dependent species. Lightning is the natural ignition source in Florida, substantiating the need for understanding lightning fire incidence. Sixteen years of lightning data (1986–2003, excluding 1987 and 2002 due to missing data) from the NASA Cloud to Ground Lightning Surveillance System and fire ignition records were used to quantify the relationship between lightning incidence and ignitions on Kennedy Space Center, Merritt Island National Wildlife Refuge, and Cape Canaveral Air Force Station. There were 230 lightning fires with an average of 14 ignitions per year, primarily in July, and only one winter ignition. Precipitation influenced the efficiency of lightning ignitions, particularly July precipitation. We found that negative polarity strikes caused the majority of ignitions. Pine flatwoods was ignited more frequently than expected given equal chance of ignition among landcover types. About half (51%) of detected fires were instantaneous ignitions and the other 49% were delayed an average of 2 days. This information is useful for paramaterizing fire regime models and for mimicking the natural fire regime through fire prescriptions on these properties and throughout the southeastern United States. These methods may be useful in fire-maintained systems globally.

Résumé : Les influences anthropogéniques ont modifié la plupart des régimes de feux. Les programmes de gestion du feu essaient souvent d'imiter les régimes de feux naturels pour conserver les combustibles et maintenir les espèces indigènes qui dépendent du feu. En Floride, la foudre est la source naturelle d'allumage, ce qui justifie la nécessité de comprendre l'incidence des feux de foudre. Seize années de données sur la foudre (1986–2003 à l'exception de 1987 et 2002 à cause de données manquantes) provenant du système de détection des éclairs nuage-sol de la NASA et de données d'allumage des feux ont été utilisées pour quantifier la relation entre l'incidence de la foudre et les allumages au Centre spatial Kennedy dans la réserve faunique nationale de Merritt Island et à la base des forces aériennes de Cap Canaveral. Il y a eu 230 feux de foudre avec une moyenne de 14 allumages par année, principalement en juillet, et seulement un allumage en hiver. La précipitation a influencé les allumages par la foudre, surtout en juillet. La majorité des allumages ont été causés par des éclairs dont la polarité était négative. Le feu a été allumé plus souvent que prévu dans les forêts de pin palustre en supposant une probabilité d'allumage égale parmi les types de couvert. Environ la moitié (51 %) des feux qui ont été détectés ont été causés par des allumages instantanés et les autres 49 % sont survenus après un délai de 2 jours. Cette information est utile pour paramétrer les modèles de régimes de feux et imiter le régime naturel de feux via des prescriptions de brûlage sur ces propriétés et dans tous le sud des États-Unis. Globalement, ces méthodes peuvent être utiles dans les écosystèmes qui dépendent du feu.

[Traduit par la Rédaction]

Introduction

The fire regime of an area is defined by its fire type, intensity (severity), size, return interval, seasonality, and spatial pattern (Christensen 1985). While fires start naturally through lightning or volcanic activity, anthropogenic ignitions such as arson and escaped incendiary fires heavily influence many fire regimes globally (Bond and van Wilgen 1996; Vigilante et al. 2004; Genton et al. 2006; Syphard et al. 2007). Changes in ignition source over time combined with fire suppression and fuel fragmentation have altered most fire regimes. Many contemporary fire regimes now only partially resemble those typical of the past. This is the case in the southeastern United States, particularly Florida, which incurs one of the highest rates of lightning incidence in North America (Orville and Huffines 2001; Murphy and Holle 2005). The natural fire regime in Florida (prior to fire suppression and fuel fragmentation by urban features) comprised frequent, lightning-ignited fires (Abrahamson and

Received 19 December 2008. Accepted 24 November 2009. Published on the NRC Research Press Web site at cjfr.nrc.ca on 30 January 2010.

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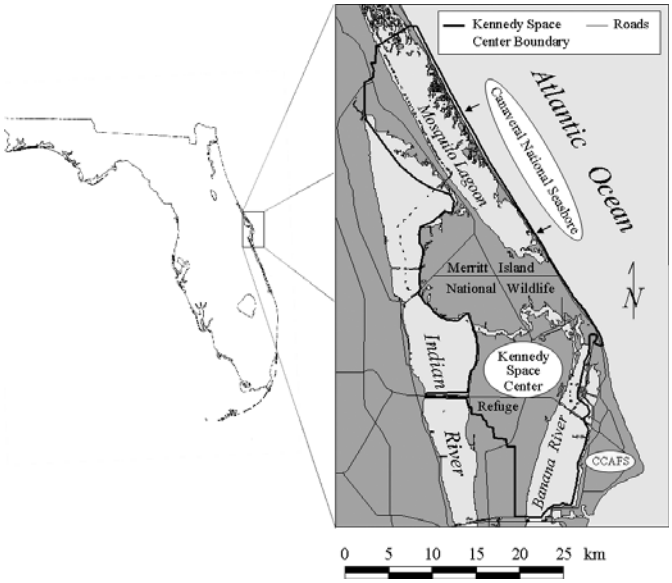
 doi:10.1139/X09-193

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



Hartnett 1990; Brewer 2006; Slocum et al. 2007). Various native species (e.g., the Florida Scrub-Jay (*Aphelocoma coerulescens*) and Highlands scrub hypericum (*Hypericum cumulicola*)) adapted and became dependent on this fire regime and are struggling with declining populations under contemporary fire regimes (Quintana-Ascencio et al. 1998; Breininger et al. 2006; Menges et al. 2006).

Fire management programs are now trying to reverse anthropogenic influences to either reduce dangerous fuel levels or restore habitat for native fire-dependent species. To restore and maintain habitat for native fire-dependent species, it is necessary to have sound, scientifically based information detailing the natural fire regime. In most areas, it may not be possible to return to a natural fire regime, but it is possible for land managers to mimic some of the processes and resulting patterns. The relationship between cloud to ground lightning and fire ignition is a fundamental component of the natural fire regime, which must be quantified so that fire and land managers can approximate natural system conditions and behaviors.

The majority of the studies detailing the relationship between cloud to ground lightning and fire ignition have taken place in the boreal forest (Flannigan and Wotton 1991; Nash and Johnson 1996; Wierzchowski et al. 2002; Larjavaara et al. 2004, 2005; Krawchuk et al. 2006; Kilinc and Beringer 2007) or other regions outside the southeastern United States (Minnich et al. 1993; Petersen and Drewa 2006). Surprisingly, there have not been any lightning fire ignition studies published in the literature that link the characteristics of cloud to ground lightning and fire ignition in Florida. However, one study detailed the spatial patterns of fire by different means of ignition, including lightning, for Florida's St. Johns River Water Management District (Genton et al. 2006). Another documented that negative polarity cloud to ground lightning strikes initiated more fires than positive polarity lightning (Mitchener and Parker 2005).

Our goal was to separate the lightning ignition component from the contemporary background anthropogenic fire regime to define the natural fire ignition regime for Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida. The managed contemporary fire regime on these properties has been delineated and described in a separate study; for details, please refer to Duncan et al. (2009). The lightning fire ignition regime that we delineated in this study includes the lightning ignition frequency, lightning ignition seasonality, lightning-ignited fire size, spatial lightning and ignition densities, and properties of lightning that ignites fires. The influence of precipitation on lightning ignition efficiency and fire size was also investigated. The information generated here is applicable for furthering our understanding of the natural lighting ignition regime and improving fire management on these federal properties throughout Florida and the southeastern United States and will serve as an example of how to isolate and quantify the natural ignition component from contemporary fire regimes worldwide.

Methods

Study site and background information

The Kennedy Space Center is 57 000 ha and is primarily managed by the US Fish and Wildlife Service as the Merritt Island National Wildlife Refuge with a smaller portion managed by the National Park Service as Canaveral National Seashore (Fig. 1). Cape Canaveral Air Force Station is 6475 ha and occupies the Cape Canaveral barrier island. Because these properties overlap to some degree and we are studying all of the federally owned area, we will use the first letter from each location and shorten the name from Kennedy Space Center – Merritt Island National Wildlife Refuge – Canaveral National Seashore – Cape Canaveral Air Force Station to KMCC. KMCC forms a barrier island complex covered with a diverse assemblage of fire-adapted terrestrial vegetative communities. Coastal strand occurs just inland of the coastal dunes and is a shrub community with saw palmetto (*Serenoa repens*), sea grape (*Coccoloba uvifera*), wax myrtle (*Myrica cerifera*), and other species being dominant. Coastal scrub occurs on neutral to alkaline sandy soils; a shrub form of live oak (*Quercus virginiana*) is the dominant species along with saw palmetto. Inland, upland xeric sites are dominated by oak scrub vegetation (*Quercus* spp.), while mesic sites are dominated by flatwoods (e.g., palmetto, staggerbrush (*Lyonia* spp.), holly (*Ilex* spp.), and an overstory of slash pine (*Pinus elliottii*). Because the landscape comprises 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 sand cordgrass (*Spartina bakeri*) and bluestem (*Andropogon* spp.), while the hardwood hammocks are dominated by live oak and laurel oak (*Quercus laurifolia*) and have a structure that is much less flammable than surrounding communities. Salt marsh borders these barrier islands and is dominated by sand cordgrass grading into saw palmetto and the flatwoods community on higher elevations. These communities are dominated by species that resprout following fire (Schmalzer 2003). Maps showing the

Fig. 2. Cloud to ground lightning frequency by year for the Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida.

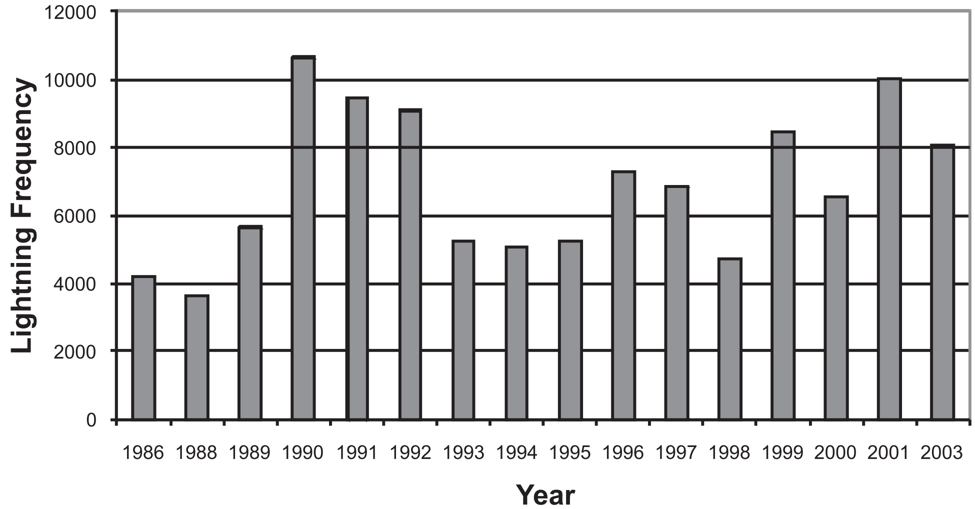
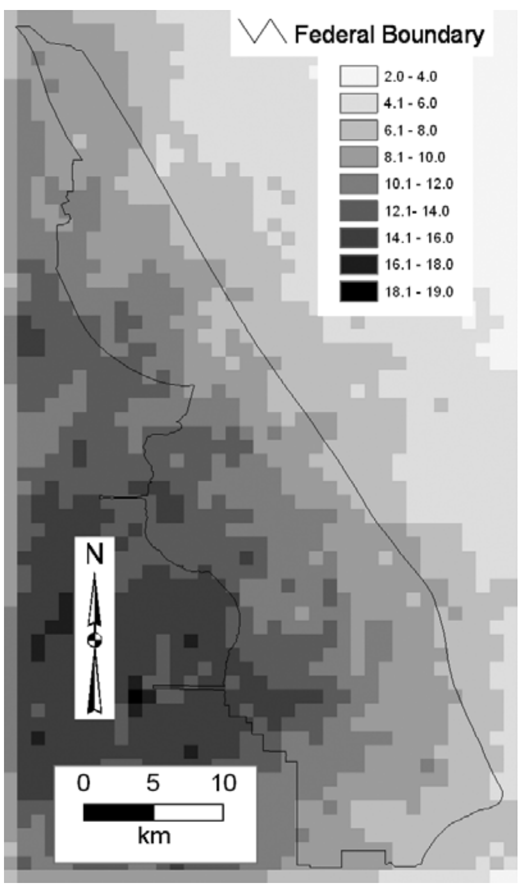


Fig. 3. Average lightning density·km^{-2} for 1986–2003 excluding 1987 and 2002 for the Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida.



distribution of these landcover types can be found in Duncan et al. (2004).

The growing season varies for each species, but the core growing season for dominants in this central Florida system is from April through early October. Early and late growing seasons are also used to describe periods in time that cross seasonal boundaries and tend to differ in humidity and precipitation. Early growing season is relatively dry and refers to the time period of April through the start of the wet convective storm season, which typically starts in late June or early July. Late growing season refers to the time period when the wet convective storm season begins (either mid- to late June or as late as mid-July in dry periods) and then ends in September or early October with the completion of the convective storm season.

Cloud to Ground Lightning Surveillance System (CGLSS)

The CGLSS records the geographic location of cloud to ground lightning strikes surrounding the KMCC region. The system comprises a sensor network located throughout east-central Florida and a position analyzer located on CCAFS where the data are maintained and stored via computer. The system has a detection rate of 98% and positional accuracy of 350 m at 95% confidence (Roeder et al. 2005). The CGLSS records date, time, strength and polarity, and location for each lightning strike. CGLSS data were mapped using ArcGIS software via the geographic coordinates, with all other data recorded as attribute information. Cloud to ground lightning locations outside the federal property boundaries of KMCC were excluded from the data set.

Fire records

A fire database containing fire name, date, location, type, cause, and size exists for all fires on KMCC and is maintained by Merritt Island National Wildlife Refuge personnel. These data have been collected since 1977. Included in this database is a type of fire referred to as a "natural out". A natural out is a fire that was ignited by lightning, went undetected while burning, and then went out on its own. These fires were recorded by periodic visual observation from helicopter surveys. Systematic helicopter surveys were suspended in 2000 due to funding constraints. However, natural outs continued to be recorded by less systematic means (occasional helicopter surveys and ground-based vis-

Fig. 4. Ignition frequency by year for the Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida.

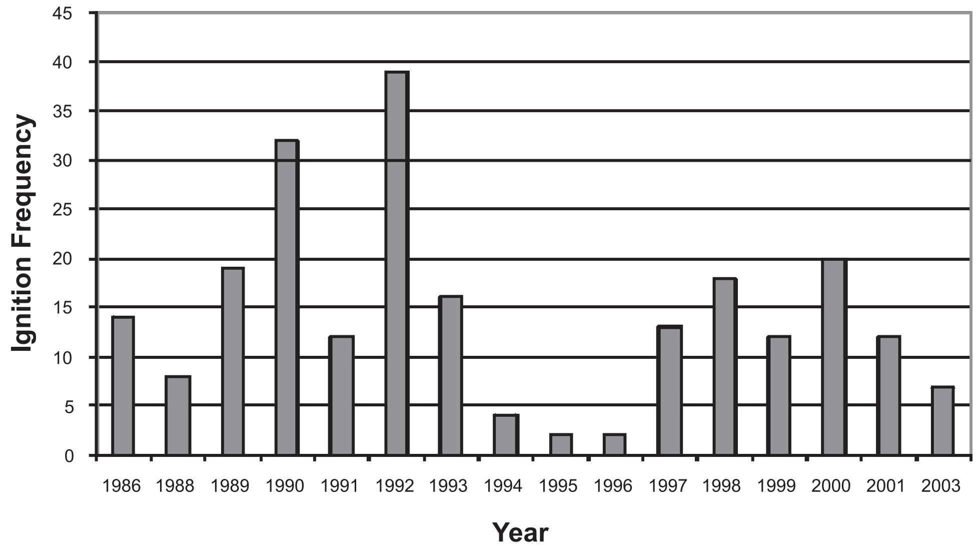
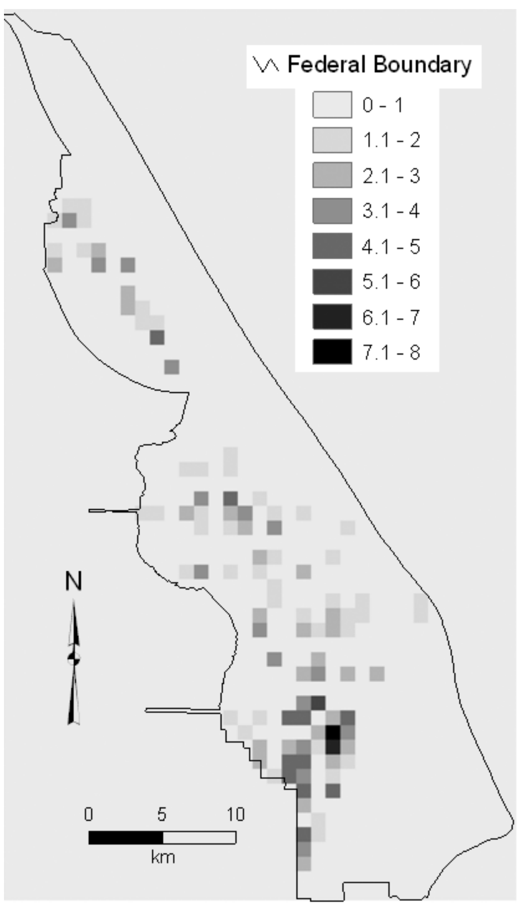


Fig. 5. Lightning ignition density·km^{-2} for 1986–2003 excluding 1987 and 2002 for the Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida.



ual observations) following the year 2000. Each fire location is recorded in the township, range, and section system with the management unit of the fire also being recorded. The township and range information for all lightning ignited fires was converted into latitude and longitude by recording the center coordinate of the corresponding section in ArcGIS. The mapped accuracy of fire centers are, at most, 0.8 km from the true position.

Lightning GIS

The CGLSS and fire data for 1986–2003, excluding 1987 and 2002 due to missing CGLSS data, were overlaid and analyzed in a GIS. Data were collected for distance, normalized signal strength (NSTR), polarity, and number of return strokes for nearest lightning strike to actual fire locations by date. NSTR is the estimated peak current of the return stroke recorded in kiloamperes and is normalized for the inferred distance to the return stroke. Included in the NSTR value is the polarity indicated by a plus or minus sign. Cloud to ground lightning density within 1 and 2 km from each actual fire was also recorded. In the cases where there were no lightning strikes recorded for the same date of a recorded fire, previous days' lightning strikes were overlaid until a reasonable match could be recorded. This delay in ignition is known as holdover time (Wotton and Martell 2005).

Lightning, lightning ignition, and lightning fire

Fire occurrence has been shown to vary among landcover types (e.g., Latham and Schlieter 1989), so a χ^2 analysis was performed to determine if ignition and lightning frequencies occurred more or less than expected for each landcover class. Landcover is used to refer to a specific category of vegetation, and fuels are used to refer to the structure of vegetation that is available for consumption by fire within or between landcover types. A 1990 landcover map was used because it represented landcover at a central time during this study and because it also represented overstory structure within its classification system; pine overstory structure is an important factor determining flammability in this system (Duncan et al. 1999, 2004). For details about the landcover types and their mapped distributions, see Duncan et al. (2004). The null hypothesis for the χ^2 analysis was no rela-

Fig. 6. Lightning ignition frequency by month for the Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida. Frequencies were summarized for ignitions that were detected/controlled and undetected ignitions that extinguished themselves (natural outs).

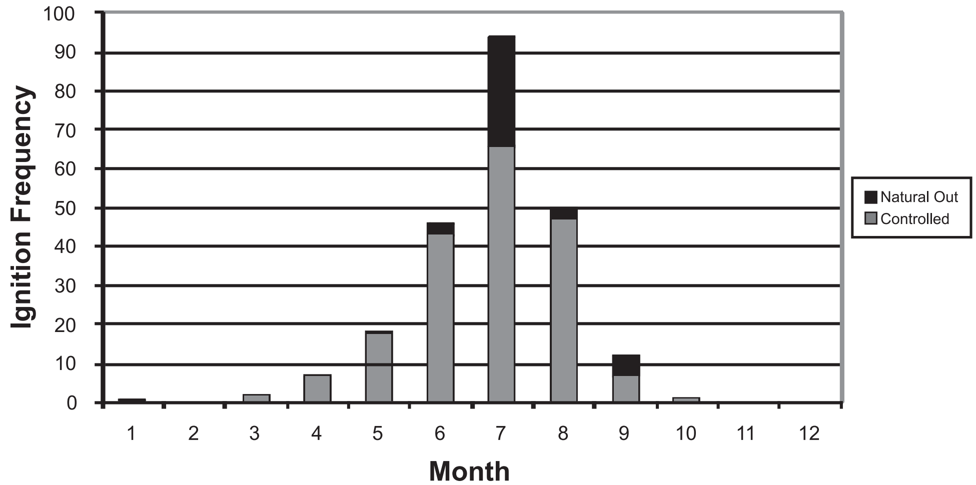


Table 1. Fire size statistics by season for the Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida.

Season	Frequency	Minimum size	Maximum size	Mean	Median
Winter (December–February)	1	0.04	0.04	0.04	0.04
Spring (March–May)	27	0.04	12.14	2.23	0.20
Summer (June–August)	189	0.04	1011.74	15.22	0.08
Fall (September–November)	13	0.04	10.12	1.58	0.04
Early Summer (1 June – 15 July)	95	0.04	1011.74	24.93	0.04
Late Summer (16 July – 31 August)	94	0.04	218.54	5.71	0.12

Note: The summer season is split in half and divided into early and late summer with the largest fires occurring during the early summer. Areas are in hectares and 0.04 ha is the minimum recorded fire size.

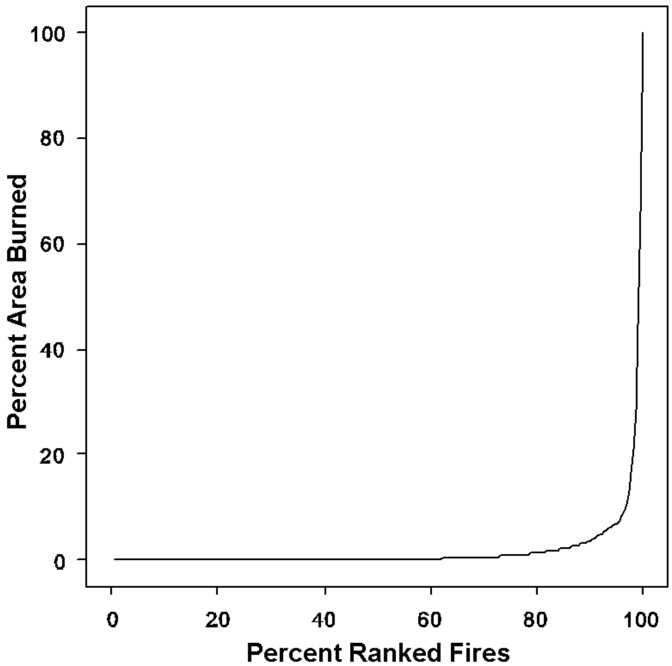
tionship between landcover category and frequency of fire/strikes. To explore the strength of these relationships (effect size), simultaneous binomial confidence intervals (Neu et al. 1974; Byers et al. 1984) were used to compare occurrence frequency of both fire and lightning strikes versus landcover type availability. The technique calculates a set of simultaneous confidence intervals using a Bonferroni correction to adjust individual alpha levels for multiple comparisons. This is useful to determine if the expected proportion of occurrence (lightning ignition type and strike type category) falls within or outside the interval. If outside the interval, we conclude that the expected and actual are significantly different.

The characteristics of lightning strikes that ignite fires have been shown to vary, so we used several techniques to investigate their relationship. Pearson correlation analysis was performed to investigate the relationship between the number of lightning strikes and the number of fires. It was also used to investigate the relationship between precipitation and the number of lightning fires. A log-linear analysis was performed to determine if the number of return strokes (multiplicity) was different between lightning strikes that ignited fires and those that did not. A null hypothesis stating that there was no difference was used. The log-linear technique was selected for this test because it is suited to count data with an error term following a Poisson distribution. A Wilcoxon rank sum test was used to look for differences between the NSTR values of lightning strikes that started fire and those that did not. The null hypothesis was that there was no difference in strike NSTR between cloud to ground lightning strikes that started fires and those that did not start fires.

Precipitation and ignition

Precipitation controls many important variables influencing fire ignition. We used both correlation analysis and linear regression to learn more about the relationship between precipitation and lightning fire ignitions. Precipitation data were used from the National Atmospheric Deposition Program collection site that is centrally located on KMCC. Because the National Atmospheric Deposition Program site is centrally located, spatial averaging was not performed. The ratio of the number of strikes to the number of ignitions (strike to ignition ratio) was regressed against precipitation for each month of the study. The natural log of the response variable was used to better meet the assumptions of the linear regression model. To further examine the importance of July precipitation, two correlations were also performed. The first correlation was between the annual number of ignitions and total July precipitation for each year and the second correlation was between the July ignition to strike ratio and total July precipitation. To highlight the importance of July preciptitation, July values were presented as a different symbol on the regression plot helping to tie the regression and the two correlations together.

Fig. 7. Proportion of ranked fires (small to large) and proportion of area burned by lightning fires for the Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida. A few large fires acounted for the majority of area burned by lightning fires.



Results

Lightning, lightning ignition, and lightning fire

The CGLSS recorded 110 300 lightning strikes over 16 years on these federal properties. The annual mean was 6892 stikes, the median was 6705 strikes, the minimum number for any year was 3647 strikes in 1988, and the maximum number was 10 648 strikes in 1990. The number of cloud to ground lightning strikes rose and fell through the duration of this study, indicating the potential for a larger, cyclical trend (Fig. 2). The majority of the cloud to ground lightning strikes, 101 678 (91.5%), were negatively charged and 8619 (8.5%) were positively charged. The spatial density of lightning strikes averaged across all years was highest on the west side of the federal property, decreasing to the east (Fig. 3).

There were 230 fires ignited by lightning within the boundaries of these federal properties for the years that correspond to the CGLSS data. The annual mean was 14 and median was 12. The minimum number of ignitions in a year was two, occurring in 1995 and 1996; the maximum was 39, occurring in 1992. The number of lightning ignitions again displayed a rising and falling trend (Fig. 4). Out of the 230 fires, 40 were natural outs, accounting for about 17% of the total. The mean number of natural outs per year was 2.5, the median was 1, the minimum was 0, and the maximum was 12. The recorded size of the natural outs was small. The mean was 0.08 ha, the median was 0.04 ha, the minimum was 0.04 ha, and the maximum was 0.8 ha. The mean size of extinguished fires was 16 ha, the median was 0.2 ha, the minimum was 0.04 ha, and the maximum was 1012 ha. The minimum area reported for all fires was 0.04 ha (0.1 acre). Holdover ignition times reveal an almost even distribution of instantaneous and delayed ignitions, 118 (51%) to 112 (49%), respectively. The maximum ignition delay was 23 days and the average was 2 days. Moderately high ignition densities occurred at the north end of the study site, with the highest densities in the southwestern portion (Fig. 5). Average lightning strike densities were 2.5 and 9 strikes·km^{-2}·day^{-1} within a 1 and a 2 km radius of each lightning ignition, respectively.

The lightning ignition frequencies were concentrated during the summer months (Fig. 6). The month of July had the greatest number of ignitions with 94, and the only winter month with any ignitions was January, with one fire. By season, winter (December–February) had one ignition, spring (March–May) had 27 ignitions, summer (June–August) had 189 ignitions, and fall (September–November) had 13 ignitions. Natural outs were concentrated during the month of July with 28 (70%) (Fig. 6). Seasonally, winter had one natural out, spring had one, summer had 33, and fall had five.

Fire size was typically small, with 220 fires smaller than 12 ha and only 10 larger in size. During the fall, winter, and spring, most lightning fires were small (Table 1). A few lightning fires accounted for the majority of total area burned by lightning ignition (Fig. 7). The majority of the large fires occurred early in the summer season. There were three very large lightning fires during this study that accounted for 36.5% of the total area burned. The first of these fires occurred on 6 July 6 1992 with a size of 486 ha and the second and third occurred on 21 June 1998 with sizes of 643 and 1012 ha, respectively.

The χ^2 test indicated significant differences between actual ignition and expected ignition (χ^2 = 329.6, df = 12, P < 0.00001) and between actual lightning strike frequency and expected lightning strike frequency in the different landcover classes (χ^2 = 1235.8, df = 12, P < 0.00001). The simultaneous confidence interval method indicated that there were slightly more fire ignitions in the disturbed uplands and forested wetlands than expected given their area (Table 2). There were significantly fewer fire ignitions in the "other" category (including the landcover types water, sand/barren, mangrove, and coastal strand), confirming that the technique performed properly due to the mostly inflammable nature of these categories. The "other" category had the largest proportion of strikes because it occupied the largest area within the study site. The lightning strike proportions and the type availability were very tightly bunched, with the largest separations (significant differences) occurring in the other, flatwoods, and forested wetlands landcover types. Fire in the flatwoods landcover type occurred much more frequently than would be expected given equal chance of ignition among landcover types.

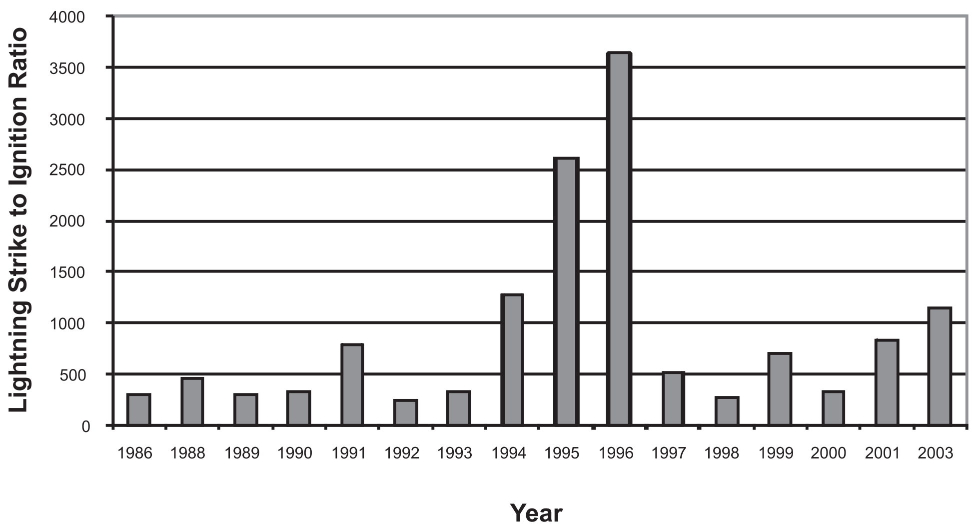
Comparing the nearest cloud to ground lightning strike and ignition location indicated that 215 (93%) of the ignitions were caused by negatively charged lightning strikes and 15 (7%) were caused by positively charged lightning. Negative polarity lightning was dominant during all seasons, with 83% of all strikes being negatively charged in winter, 88% in spring, 93% in summer, and 90% in fall. The multiplicity (number of strokes per flash) had an average of 2.4, a median of 2.0, and a maximum of 14 for strikes that initi-

Table 2. Proportions of landcover type, cloud to ground lightning strikes, and lightning-ignited fires occurring on the Kennedy Space Center, Merritt Island National Wildlife refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida.

Landcover	Proportion of landcover	Proportion of strikes	95% CI	Proportion of fires	95% CI
Urban	0.050	0.049	0.048, 0.050	0.067	0.047, 0.087
Agriculture	0.012	**0.015**	0.014, 0.015	**0.032**	0.018, 0.046
Flatwoods	0.080	**0.090**	0.089, 0.092	**0.301**	0.265, 0.338
Scrub	0.101	0.096	0.095, 0.097	0.112	0.087, 0.137
Hammock	0.068	**0.076**	0.075, 0.077	0.089	0.067, 0.112
Disturbed uplands	0.021	0.022	0.021, 0.022	**0.045**	0.029, 0.061
Forested wetlands	0.039	**0.045**	0.044, 0.046	**0.093**	0.070, 0.116
Freshwater marsh	0.057	**0.067**	0.066, 0.068	0.058	0.039, 0.076
Saltwater marsh	0.073	**0.078**	0.076, 0.079	0.067	0.047, 0.087
Disturbed marsh	0.019	**0.022**	0.021, 0.022	0.026	0.013, 0.038
Spoil	0.027	0.028	0.027, 0.028	0.022	0.011, 0.034
Other	0.452	0.413	0.411, 0.415	0.087	0.064, 0.109

Note: Confidence intervals (CI) are given for lightning strikes and lightning-ignited fires showing if they differed significantly from that expected based on proportion of each landcover type. Proportions in bold have 95% CIs above and those underlined below the proportions of landcover type.

Fig. 8. Annual lightning strike to ignition ratio for the Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida. The lightning strike to ignition ratio is derived by dividing the total number of cloud to ground lightning strikes by the total number of ignitions for each year.



ated fires. The number of return strokes from lightning strikes that started fires and the number of those that did not were significantly different (F = 4.27, P = 0.0387). NSTR was also significantly different for lightning strikes that started fire and for those that did not (W = 5 935 327, P = 0.0026). The NSTR values were lower (more negative) for non-fire-igniting lightning strikes.

Precipitation, ignition, and lightning fire

The ratio of cloud to ground lightning strikes to ignitions for each year varied, with a mean of 881, a median of 491, a minimum of 233 in 1992, and and a maximum of 3647 in 1996. There were a few years that had an inordinately large ratio of strikes to ignitions (Fig. 8). These same years had above-average precipitation (Fig. 9). The monthly ratio of cloud to ground strikes had a mean of 812, a median of 536, a minimum in July of 309, and a maximum in October of 2153 (Fig. 10). The annual number of cloud to ground lightning strikes and the number of actual ignitions were normally distributed (Shapiro–Wilk test, P = 0.488, P = 0.083) and not significantly correlated (r = 0.398, P = 0.126).

Summertime precipitation variability is highest during the early summer season (Table 3). The month of June has the smallest and greatest precipitation total of the summer months, while early July is dryer than late July. The annual number of lightning ignitions and July precipitation were normally distributed (Shapiro–Wilk test, P = 0.132, P = 0.276) and negatively correlated (r = –0.719, P = 0.002). The July lightning strike to ignition ratio was not normally distributed (Shapiro–Wilk test, P = 0.032) and the ratio was correlated with July precipitation (Spearman's rank, r = 0.64, P = 0.015). Regressing the natural log of the monthly strike to ignition ratio versus monthly precipitation revealed that lightning ignition efficiency declines with increasing precipitation (Fig. 11). Residuals from this model met statistical assumptions and had an R^2 = 0.36, indicating a structural relationship in the data.

Fig. 9. Precipitation above and below the mean as measured at the National Atmospheric Deposition Program collection site for the Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida. The mean precipitation value for the years 1986–2003 excluding 1987 and 2002 is 127.9.

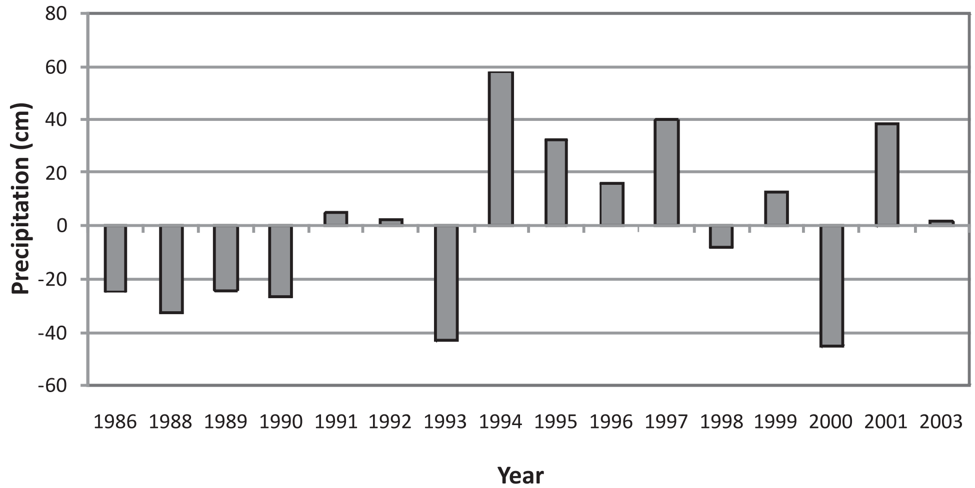


Fig. 10. Monthly lightning strike to ignition ratio for the Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida. The lightning strike to ignition ratio is derived by dividing the total number of cloud to ground lightning strikes by the total number of ignitions for each month. There were no ignitions during February, November, and December.

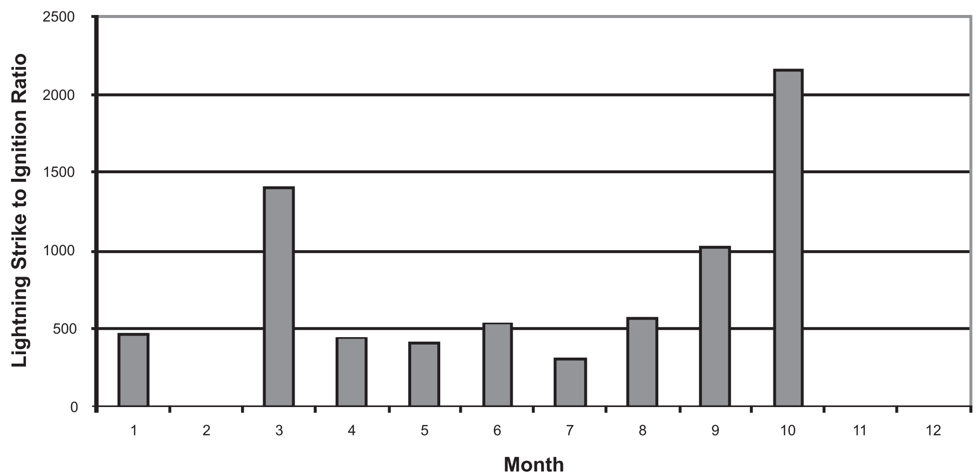


Table 3. Precipitation amounts (cm) for different time periods during the summer for Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida, from 1986 to 2003 excluding 1987 and 2002.

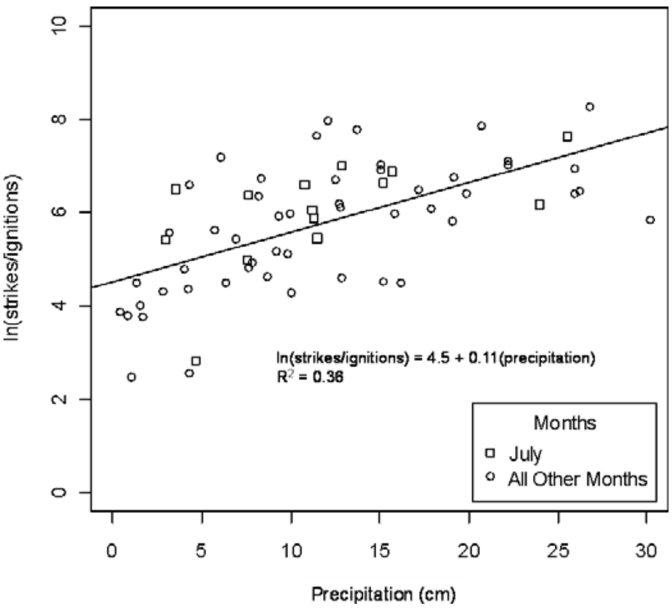
Time period	Minimum	Maximum	Median	Mean	Variability	SD
June	1.52	30.23	17.54	17.07	73.87	8.59
July	2.95	28.96	11.34	12.16	53.46	7.31
August	4.27	25.96	13.75	14.62	46.58	6.83
1–15 July	0.00	11.96	5.35	5.47	13.25	3.64
16–31 July	0.20	19.69	5.79	6.70	29.45	5.43
1 June – 15 July	7.95	39.01	19.20	22.54	104.91	10.24
16 July – 31 August	8.41	43.87	20.84	21.32	67.23	8.20

Discussion

Lightning, lightning ignition, and lightning fire

Areas with the highest lightning incidence did not correspond directly to areas with the highest ignition incidence. The western side of the federal properties has the highest average lightning density and therefore the greatest overall ignition potential. The greatest ignition density, however, is found where there is a convergence of highly flammable landcover and relatively high lightning incidence. Areas of high ignition density in the north and the highest density in the southwest corner of the study area correspond to areas

Fig. 11. Regression plot displaying the relationship between the natural log of the monthly strike to ignition ratio and monthly precipitation for the Kennedy Space Center, Merritt Island National Wildlife Refuge, Canaveral National Seashore, and Cape Canaveral Air Force Station, Florida. July is a particularly important month, so July values are displayed with a symbol different from that of other months.



comprising pine flatwoods landcover. The pine flatwoods landcover type displayed significantly higher than expected ignition incidence. In general, the difference between the amount of actual lightning strikes per landcover category and expected is very small. The confidence intervals are tight because the lightning strike sample size is extremely large. The largest differences are in the other category (less strikes than expected), with flatwoods, freshwater marsh, and hammocks (more strikes than expected) following in that order. There are slightly more lightning strikes in each of the flatwoods, hammocks, and freshwater marsh categories, but in the actual ignitions, flatwoods is the only one of these three categories to have a greatly larger amount of actual ignitions. This finding may be supportive of earlier studies (Mitchener and Parker 2005) that found that lightning density was not the dominant factor determining fire ignition within national forests of the southeastern United States. Pine fuel types in general have been found to be highly susceptible to lightning ignition (Latham and Schlieter 1989), while flatwoods flammability has long been noted due to its pine overstory and flammable understory (Myers 1990; Duncan et al. 1999).

In this study, negative polarity lightning strikes overwhelmingly started fires. This differs from early studies asserting that lightning with long continuing current started fires and that because positive strikes have a higher probability of long continuing current, positive strikes had greater ignition potential (Fuquay et al. 1972; Flannigan and Wotton 1991). More information is now available suggesting that negative lightning polarity is an important ignition source igniting fires in many ecosystems (e.g., Flannigan and Wotton 1991; Orville and Silver 1997; Larjavaara et al. 2005; Mitchener and Parker 2005). Lightning polarity varies geographically and seasonally in North America (Orville and Silver 1997). Negative polarity lightning is the dominant polarity in the southeast. In this study, negative polarity is dominant even during the winter season, and the annual background polarity values are similar to the ignition proportions for both positive and negative polarities. Thus, lightning ignitions are occurring with the same proportions as available lightning polarity. Also, lightning strikes initiating fires are negatively polarized but they do not possess a large negative magnitude. Negative strike multiplicity has been shown to be the highest in the southeastern United States (Orville 1994). Multiplicity has been linked with ignition probabilities (Flannigan and Wotton 1991; Larjavaara et al. 2005). Different results have been found, however. Flannigan and Wotton (1991) found that the average negative multiplicity was a very important predictor and correlated with lightning ignition, while Larjavaara et al. (2005) showed that higher multiplicity decreased ignition probability. Multiplicity values that ignited fires in this study were significantly lower than background values.

Precipitation, ignition, and lightning fire

Fewer lightning strikes are needed to ignite fires during dry, rain-free periods. For the central Florida landscape, this was most pronounced in July. The years of 1994, 1995, and 1996 required many more strikes than the average (881) to ignite a single fire. The precipitation records on Merritt Island indicate that these years were all above average and are the only consecutive years during this study with above-average precipitation. The year of 1997 was also an above-average year for precipitation but fewer than the average lightning strikes were needed to ignite a single fire. This year was an El Niño year and the majority of its precipitation fell during November and December. Up to November 1997 was actually fairly dry, with Palmer hydrologic drought index values consistently in the –1 to –2 range, indicating dry conditions (the index ranges from –6 to +6 representing dry to wet, respectively). This explains why there was a drop in the lightning strike to ignition ratio for 1997. These findings were supported by the regression between monthly precipitation and monthly strike to ignition ratios, the correlation between July strike to ignition ratio and July precipitation, and the negative correlation between the number of ignitions and July precipitation. Generally, when it has rained, more strikes are required to ignite fires. This is especially true for July; when July is wet, it takes more lightning strikes to ignite fires, and when July is dry, fewer strikes are needed to ignite fires. July rainfall is particularly important because it corresponds to the peak in lightning incidence. This trend is clearly visible in the monthly strike to ignition ratio data. The fewest strikes are required to ignite fires in July just after the annual dry period, and the maximum number of strikes is required to ignite fires in October after the summer wet season (Mailander 1990).

The majority of lightning fires occurred during the wet season, and they were small, supporting the conclusion that most fires in the natural system were small. Natural outs greatly contributed to this trend. The resources necessary to systematically document natural out fires are significant and generally out of reach for most organizations. As a result, recording of small fires, particularly natural outs, is usually lacking in empirical data sets (Nash and Johnson 1996; Cui and Perera 2008). Natural outs were all very small and the overwhelming majority occurred during the wet and humid growing season. Presumably, the wet, humid conditions at this time of year controlled the size of these fires and they went undetected. In light of the delayed (holdover) ignitions, it is reasonable to assume that not all of these fires would have stayed small. Some of these small fires may have started and burned until conditions became unfavorable, entered a smoldering state, and then reignited when conditions became favorable, ultimately growing to be larger fires. Most of the fires (83%) in this study were controlled. Of the fires that were controlled, the mean fire size was relatively small (mean of 16 ha), indicating that fire suppression was successful at controlling most fires before they became large and that many natural fires would have at least been 16 ha in size or larger. There were three very large lightning fires that contributed most of the area burned, and all of these fires were during the first half of the growing season. The two largest fires occurred during the very dry La Niña period of 1998. During the early growing season, dry periods are intermixed with wet periods, creating a large amount of precipitation variation when compared with the late growing season. The amount of actual precipitation is very comparable between the early and late growing season, but the later part is more consistently wet, limiting favorable conditions for large fires. It is during these dry early season periods that the large fires occurred. The month of June had the least and greatest amount of rain during the duration of this study.

There was a large size discrepancy between the fires that commonly occurred (under wet and average meteorological conditions) and those that occurred during the less frequent drought periods. Evidence suggests that natural, large fires occurred in Florida during the drought periods in the early growing season (Brenner 1991; Beckage et al. 2005). El Niño Southern Oscillation patterns are strongly linked to this trend, and the most extreme fires likely occurred during these climatic events (Brenner 1991; Beckage and Platt 2003; Beckage et al. 2003), as indicated in this study. It is no coincidence that most fires in this study were in the small to medium size range. This is because these fires occurred under average meteorological conditions, making them relatively easy to control, as opposed to the ones during drought periods that were difficult to control, hence their large size. Evidence for the medium-sized fires (under 400 ha) is limited because fire suppression and control appear to be most effective in this size class. The smallest fires (natural outs) are not influenced by suppression efforts and the largest fires burn under extreme meteorological conditions when control efforts are less effective. Under the natural fire regime, large fires would have been infrequent relative to small and medium fires. These frequent small- and medium-sized fires would have created a mosaic of different-aged fuels on the natural landscape. This mosaic of fuels would have greatly influenced flammability and propensity to burn (Myers 1990; Breininger et al. 2002), ultimately influencing fire patterns through a feedback of fuels ready to carry fire based on structure, referred to as self-organization (Cui and Perera 2008). These burn patterns would have created a complex physical arrangement of vegetation influencing habitat quality for fire-dependent species, such as the Florida Scrub-Jay (Breininger and Carter 2003). The Florida Scrub-Jay's demography peaks in habitat with sand openings and oak scrub heights of approximately 120 cm (Breininger et al. 2006). These are very specific conditions that do not persist on the landscape without frequent fire (Schmalzer 2003). For these conditions to persist through time, there must be a rotation of vegetation into this structure on the landscape.

General considerations and management implications

A caveat of this study is that fuel fragmentation by roads, buildings, agriculture, and exotic species has influenced the flammability of the landscape in this study. The influence of fuel fragmentation on fire spread and fire size was modeled in this landscape; it was found to reduce both (Duncan and Schmalzer 2004). The removal of fuels and the replacement of flammable native fuels by less flammable exotic species potentially influenced both the number of fire starts and the rate of fire spread, affecting fire size. Another consideration is that natural fire regimes are not static but are dynamic through time. In this context, the results here represent a reasonable approximation of the recent historic natural fire regime within some range of variability.

Florida, like other fire-adapted regions of the world, has many conservation areas designed to protect native species but a limited amount of scientifically sound information on which land managers can base fire management decisions. Fire managers wanting to mimic the results of the natural fire regime to benefit native fire-dependent species will benefit from the information generated by this study. A primary example is that the current managed fire regime burns the maximum area in November (Duncan et al. 2009) and this study shows that there was not a single lightning ignition for the duration of this study during November. The influence of fire season could have a profound impact on the demography of some species (Outcalt 1994) and as an example should be considered by fire managers. The number, timing, size, and location of natural fires are all important references for fire managers attempting to mimic the natural fire regimes in fire-maintained systems worldwide.

Conclusion

This study isolated the natural lightning ignition regime component from the background managed fire regime including prescribed and lightning ignitions (see Duncan et al. (2009) for description and details of the contemporary managed fire regime) to answer many long-standing questions about the relationship between cloud to ground lightning and fire ignition in this region. We know that the natural fire regime maintained the native flora and fauna and mimicking it is an important step to sustaining viable populations of native species in fire-dependent systems. 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). This study is directly relevant for existing fire management programs on these properties, and throughout the southeastern United States, it will help parameterize models used to optimize future fire management (e.g., define ignition frequency, density location, and seasonality needed as inputs to fire regime models) and will add additional information to the growing number of studies quantifying the environmental factors driving lightning fire initiation.

Acknowledgements

This study was conducted under NASA contract NAS10-12180. We thank Kelly Gorman, Burton Summerfield, Steven Brisbin, John Weishampel, Pedro Quintana-Ascencio, Reed Noss, Frank Davis, Paul Schmalzer, Tammy Foster, John Drese, and Danny Hunt for their help, guidance, and support.

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