



Dynamics of gaps created by burning in Florida oak–saw palmetto (*Quercus*, Fagaceae–*Serenoa repens*, Arecaceae) scrub^{1,2}

Authors: Schmalzer, Paul A., and Foster, Tammy E.

Source: The Journal of the Torrey Botanical Society, 145(3) : 250-262

Published By: Torrey Botanical Society

URL: <https://doi.org/10.3159/TORREY-D-17-00037.1>

BioOne Complete ([complete.BioOne.org](https://complete.bioone.org)) is a full-text database of 200 subscribed and open-access titles in the biological, ecological, and environmental sciences published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Complete website, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at www.bioone.org/terms-of-use.

Usage of BioOne Complete content is strictly limited to personal, educational, and non - commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

Dynamics of gaps created by burning in Florida oak–saw palmetto (*Quercus*, Fagaceae–*Serenoa repens*, Arecaceae) scrub^{1,2}

Paul A. Schmalzer³ and Tammy E. Foster

Ecological Program, Mail Code IMSS-300
Kennedy Space Center, Florida 32899

Abstract. Sandy gaps in the shrub matrix of oak (*Quercus* L.)–saw palmetto (*Serenoa repens* (W. Bartram) Small) scrub are created by fire but typically close quickly because of rapid regrowth. Such gaps are important habitat features for rare scrub flora and fauna and appear to have been more common in the historical landscape. We followed, from 1993 to 2016, the dynamics of 12 gaps (32.2–98.1 m²) created by burning slash piles as part of restoration of long-unburned scrub. Gaps closed slowly, primarily by canopy spread of oaks around the gaps. In the absence of subsequent fire, gaps closed within approximately 12 yr. When burned a second or third time, gap area increased to near the initial after-burn size but then declined in area more rapidly than after the initial fire. Vegetation that reestablished in gaps differed from that of the scrub matrix in having less cover of scrub oaks, less cover of *S. repens* > 0.5 m, greater cover of native shrubs and forbs > 0.5 m, and more bare ground. Soil heating from slash-pile burning killed the roots and rhizomes from which scrub oaks, *Serenoa*, and ericaceous shrubs sprout; this altered and slowed the after-fire recovery.

Key words: *Quercus*, restoration, scrub oaks, *Serenoa*, slash pile, sprouting

Natural disturbance, such as fires, windstorms, and floods, affects vegetation structure and composition at multiple spatial and temporal scales (White 1979, Pickett and White 1985, Mitchell 2013). Disturbance regimes are integral to the survival of many species and the maintenance of diversity (Gardner and Engelhardt 2008). Gaps—openings in a forest canopy where one tree died and recruitment of new individuals occurs (Watt 1947)—are disturbances that are small, relative to the vegetation matrix. Canopy gaps influence regeneration and species diversity in temperate, tropical, and boreal forests (Brokaw 1985, Runkle 1985, Platt and Strong 1989, Denslow and Spies

1990, Spies *et al.* 1990, Yamamoto 1992, Brokaw and Busing 2000, McCarthy 2001, Martins and Rodrigues 2002, Rantis and Johnson 2002, Kwit and Platt 2003); they are recognized as important in forest systems worldwide (Muscolo *et al.* 2014, Zhu *et al.* 2014, Buettel *et al.* 2017). Gaps contribute to greater herbaceous diversity in forested wetlands (Anderson and Leopold 2002) and herbaceous-layer composition and diversity in tropical forests (Dirzo *et al.* 1992). Gap formation may be the primary disturbance (Runkle 1998) or may interact with more-widespread disturbances, such as typhoons (Yao *et al.* 2015), ice storms (Nagel *et al.* 2017), or fire (Cannon *et al.* 2017). Fire is an important disturbance in vegetation worldwide (Bond and van Wilgen 1996, Bond and Keeley 2005).

Gaps in the prevailing vegetation matrix also influence vegetation in nonforested systems, including shrublands (Dickinson *et al.* 1993), woodlands (Pecot *et al.* 2007), and grasslands (Tozer *et al.* 2008, Franzese *et al.* 2009). Crawford and Young (1998) found species richness to be greater in gaps than it was in a shrub thicket. Mounds created by badgers in a prairie supported fugitive plants (Platt and Weis 1977). Patches of bare ground influenced herb and shrub establishment in subalpine heathland and grassland (Williams 1992). Oak survival and growth in an oak savanna–dry forest matrix was influenced by the interaction between gaps and fire (Rebertus and Burns 1997), and pine growth increased in gaps in a pine savanna (McGuire *et al.* 2001). In California

¹ This study was conducted under National Aeronautics and Space Administration contracts NAS10-11624, NAS10-12180, NAS10-02001, NNKO8OQ01C, and NNK16OB01C. We thank R. Schaub and V. Larson for marking the gaps initially, S. Turek and C. Dunlevy for field assistance early in the project, and the Student Life Sciences Training Program classes from 1995 to 2005 for assistance in collecting gap data. The fire management staff of Merritt Island National Wildlife Refuge conducted prescribed burns on the site. We thank Eric Menges and several reviewers for their comments.

² Supplemental material for this article is online at <http://dx.doi.org/10.3159/TORREY-D-17-00037.1>.

³ Author for correspondence: paul.a.schmalzer@nasa.gov.

doi: 10.3159/TORREY-D-17-00037.1

©Copyright 2018 by The Torrey Botanical Society

Received for publication August 14, 2017, and in revised form April 17, 2018; first published August 10, 2018.

chaparral, Keeley *et al.* (2016) found obligate-seeding species favored by large gaps.

Disturbance of belowground biomass can lead to the formation of aboveground gaps. In an old field, Cahill and Casper (2002) found that canopy gaps corresponded to gaps in belowground biomass. Persistent openings in New Jersey pinelands formed where disturbance, probably fire, removed the organic horizon and the dense roots and rhizomes contained in it (Ehrenfeld *et al.* 1995).

Florida Scrub. Florida scrub is a shrub community on well-drained, infertile, sandy soils, in which scrub oaks (*Quercus geminata* Small, *Quercus myrtifolia* Willd., *Quercus chapmanii* Sarg., *Quercus inopina* Ashe), Florida rosemary (*Ceratiola ericoides* Michx.), repent palms (*Sereinoa repens* (W. Bartram) Small, *Sabal etonia* Swingle ex Nash), and ericaceous shrubs predominate (Myers 1990). Florida scrub is known for the number of rare, endemic plants it contains (Christman and Judd 1990, Menges 1999, Stout 2001), and it is habitat for a number of rare, threatened, or endangered fauna (Myers 1990, Menges 1999).

Florida scrub is characterized by periodic, intense fire (Abrahamson and Hartnett 1990, Myers 1990). Fire is an important disturbance in scrub; vegetation composition in scrub is influenced by fire, depth to water table, and soils (Myers 1990, Menges 1999). Fire behavior and effects are heterogeneous at the landscape scale (Turner *et al.* 1994, 2003) within stands of vegetation (Odion and Davis 2000) and at fine spatial scales of ≤ 1 m (Thaxton and Platt 2006, O'Brien *et al.* 2016). Variation in fuels contributes to heterogeneity in fire behavior and effects (Mitchell *et al.* 2009).

Gaps—open, sandy areas—are critical microhabitat features for many of the rare scrub plants (Menges and Hawkes 1998, Menges 1999, Menges *et al.* 2008) and scrub fauna (Greenberg *et al.* 1994, Hokit *et al.* 1999, Carrel 2003, Breininger *et al.* 2014). The microclimate of those gaps may differ from the surrounding scrub matrix; for example, Weekley *et al.* (2007) found soil moisture to be greater in gaps than it was in the scrub matrix in several scrub types.

Gaps in Florida rosemary scrub may persist for long periods after fire (Hawkes and Menges 1996, Menges *et al.* 2008). *Ceratiola ericoides* is killed by fire, reestablishes by seed, and grows more slowly than sprouting scrub oaks (Johnson 1982,

Menges *et al.* 2008). In addition, *Ceratiola* sp. produces allelochemicals that depress germination of co-occurring plant species (Hunter and Menges 2002, Hewitt and Menges 2008). In contrast, gaps in oak–saw palmetto scrub or scrubby flatwoods, close more rapidly after fire, where postfire regeneration is primarily by sprouting of clonal species (Abrahamson 1984a, b; Schmalzer and Hinkle 1992; Young and Menges 1999; Schmalzer 2003; Dee and Menges 2014). However, gaps in scrubby flatwoods are important for regeneration and persistence of some species (Young and Menges 1999, Dee and Menges 2014).

At the landscape scale, gaps in Florida scrub were historically more abundant before landscape fragmentation and fire suppression; prescribed fire management has restored gaps in some sites but not others (Duncan *et al.* 1999).

Here, we examined the dynamics of aboveground gaps in oak–saw palmetto scrub that were established by burning of piles during restoration of long-unburned scrub to restore habitat for the threatened Florida scrub-jay (*Aphelocoma coerulescens*; Schmalzer *et al.* 1994, Breininger *et al.* 2014). Our objectives were (a) to determine the persistence of these created gaps, (b) to identify the vegetation composition within the gaps, and (c) to compare the vegetation composition in the gaps to vegetation in the surrounding scrub matrix. We followed the extent and vegetation composition of a set of 12 of these gaps through an unburned recovery period of 10 yr. We also observed how gaps changed after second and third fires up until 2016. Because gaps are a critical habitat feature for many scrub species, it is important to understand how gaps created by management practices change over time.

Materials and Methods. This study was conducted in the northern section of the Kennedy Space Center/Merritt Island National Wildlife Refuge (KSC/MINWR) in the Shiloh area (28°38'N, 80°42'W). Two adjacent stands of long-unburned oak–saw palmetto scrub, separated by a sand road, were selected for restoration as part of the scrub-habitat compensation plan for KSC/MINWR (Schmalzer *et al.* 1994). The northern stand was about 12.1 ha, and the southern stand was 9.1 ha.

Before mechanical treatment, 20 line-intercept transects (15 m long; Mueller-Dombois and Ellenberg 1974) were established and sampled in

Table 1. History of the Shiloh scrub restoration site.

Year	Event
1992–1993	Transects ($N = 20$) established and sampled before treatment (1992). Scrub cut and piled. Burned in November 1993. Dimensions of 12 gaps delimited.
1994–2002	Transects (matrix) resampled 7, 16, 24, 30, 36, 48, 60, 72, 84, 96, and 108 mo after the burn.
1995–2003	Gaps sampled annually in June ($N = 12$).
May 2004	Prescribed burn: seven gaps burned, four not burned, one cut and not burned; eight transects in north section burned, two not burned, south section not burned.
2004–2007	Gaps sampled annually in June ($N = 11$).
May 2005	Prescribed burn of southern section: four transects burned, six not burned, no gaps burned.
2005–2007	Transects in northern section sampled annually in May.
May 2008	Prescribed burn: six gaps burned (two partially), five not burned; eight transects in northern section burned at least partially, seven transects in southern section burned at least partially.
2008–2012	Gaps sampled annually in June ($N = 11$).
2009–2012	Transects in both section sampled annually in May.
January 2013	Prescribed burn: five gaps burned (four partially), six not burned; two transects in northern section burned partially.
2013–2016	Gaps sampled annually in June ($N = 11$). Transects in both sections sampled annually in May.

the scrub matrix in 1992; 10 transects were north and 10 south of the sand road. Cover was measured to the nearest 5 cm by species in two height strata, > 0.5 m and < 0.5 m. Vegetation transects in the scrub matrix were sampled from 1994 through 2016 (Table 1).

The scrub matrix was dominated by scrub oaks (*Q. geminata*, *Q. myrtifolia*, and *Q. chapmanii*), *Serenoa repens*, and ericaceous shrubs, before treatment (Schmalzer *et al.* 1994). Initial vegetation height was 4.2 m north and 3.8 m south of the sand road. Soils were mapped as Paola fine sand, a Spodic Quartzipsamments (Huckle *et al.* 1974). The vegetation height and structure were indicative of scrub long unburned because of a combination of landscape fragmentation and fire suppression (Schmalzer *et al.* 1994). Subsequent dating of basal sections of *Q. myrtifolia* cut during sampling in 1992, before treatment, gave an age range of 22–53 yr north and 13–33 yr south of the sand road.

Because of the large stature of the scrub oaks at this site, a D6 tractor (Caterpillar, Peoria, IL) with a V-blade was used to cut the trees between January and March 1993. The resulting fuel bed had a high percentage of heavy fuels consisting of oak stems with basal diameters of 12–20 cm. These were left scattered to dry, then some of the heavy fuels were piled to enhance complete burning. Prescribed burns were conducted in early November 1993. The prescribed burn of the northern section was less complete (60–70%, November 1, 1993) than the southern section (95%, November 3, 1993), but the slash piles burned completely in both fires (Schmalzer *et al.* 1994).

The areas in which the slash piles burned completely left behind aboveground gaps in the scrub-vegetation matrix. The dimensions of 12 gaps were delineated after the fire, 8 in the northern section and 4 in the southern section. We sampled the gaps annually from 1995 to 2016. Gaps were approximately elliptical in shape, and area was estimated based on the lengths of the major and minor axes (Runkle 1992, Schliemann and Bockheim 2011). At each sampling, we determined the length of each axis that remained open (defined as not covered by continuous woody vegetation). The major axis of each gap was used as a line-intercept transect (Mueller-Dombois and Ellenberg 1974), and vegetation cover was determined by species each year in two height strata, > 0.5 m and < 0.5 m.

The northern section of the site burned again in May 2004 (Table 1) when seven gaps burned. One gap in the southern section of the site was disturbed by roller-chopping but not burned and was dropped from further sampling. Prescribed fires in 2008 and 2013 burned some gaps (Table 1). Some scrub-matrix transects were burned in 2004, 2005, 2008, or 2013 (Table 1).

Native and introduced species of similar life forms were classified into six plant groups (Table 2) to follow dynamics of vegetation change over time and to compare the vegetation composition of the gaps to the scrub matrix. That grouping was necessary because of the large number of individual species. Taxonomic nomenclature follows Wunderlin and Hansen (2011). We used linear models to determine how gaps and time-since-fire affected the percentage of cover for plant groups in

Table 2. Plant groups in the Shiloh scrub matrix and gaps.

Group	Taxa
Scrub oaks (ScrubOak)	<i>Quercus chapmanii</i> , <i>Q. geminata</i> , <i>Q. myrtifolia</i>
Woody vines (WoodVine)	<i>Smilax auriculata</i> , <i>Vitis rotundifolia</i>
Native shrubs (NatShrub) (not scrub oaks or <i>Serenoa</i>)	<i>Asimina obovata</i> , <i>Baccharis halimifolia</i> , <i>Bejaria racemosa</i> , <i>Callicarpa americana</i> , <i>Carya floridana</i> , <i>Diospyros virginiana</i> , <i>Gaylussacia dumosa</i> , <i>Hypericum tetrapetalum</i> , <i>Ilex glabra</i> , <i>Licania michauxii</i> , <i>Lyonia ferruginea</i> , <i>L. fruticosa</i> , <i>L. lucida</i> , <i>Myrica cerifera</i> , <i>Osmanthus americanus</i> , <i>Persea borbonia</i> , <i>Quercus laurifolia</i> , <i>Rhus copallinum</i> , <i>Rubus</i> spp., <i>Sambucus nigra</i> subsp. <i>canadensis</i> , <i>Vaccinium myrsinites</i> , <i>V. stamineum</i> , <i>Ximena americana</i> , <i>Zanthoxylum clava-herculis</i>
Exotic grasses (ExoGrass)	<i>Melinis repens</i> , <i>Panicum maximum</i> , <i>Paspalum urvillei</i>
Native grasses (NatGrass)	<i>Andropogon</i> spp., <i>Dichanthelium</i> spp., <i>Digitaria ciliaris</i> , <i>Eustachys petraea</i> , <i>Paspalum</i> spp., <i>Setaria parviflora</i>
Native forbs (NatForb)	<i>Ambrosia artemisiifolia</i> , <i>Bulbostylis</i> spp., <i>Chamaecrista fasciculata</i> , <i>Chamaecrista</i> spp., <i>Chamaesyce maculata</i> , <i>Clitoria mariana</i> , <i>Conyza canadensis</i> , <i>Cyperus ovatus</i> , <i>Erechtites hieracifolia</i> , <i>Eupatorium capillifolium</i> , <i>Galactia elliotii</i> , <i>G. volubilis</i> , <i>Gamochaeta antillana</i> , <i>Heterotheca subaxillaris</i> , <i>Linaria canadensis</i> , <i>Lupinus diffusus</i> , <i>Mikania</i> spp., <i>Opuntia humifusa</i> , <i>Passiflora incarnata</i> , <i>Phoradendron leucarpum</i> , <i>Physalis walteri</i> , <i>Phytolacca americana</i> , <i>Pteridium aquilinum</i> , <i>Scleria triglomerata</i> , <i>Seymeria pectinata</i> , <i>Solidago odora</i> var. <i>chapmanii</i> , <i>Stillingia sylvatica</i> , <i>Tillandsia recurvata</i> , <i>Tillandsia usneoides</i>

both strata (> 0.5 m and < 0.5 m) and how gaps, time-since-fire, and strata affected total cover using R software (R Foundation for Statistical Computing, Vienna, Austria). Because of the large number of zeros in the data set, the residuals of the models were not normal; the model point estimates should still be unbiased, but the variance may be underestimated. We used linear regression to examine changes in opening area over time (SPSS Statistics, version 24; IBM, Armonk, NY).

Results. RESPONSES AFTER FIRST BURN. The initial area of gaps ranged from 32.2 to 98.1 m², with a mean of 55.6 m². The area remaining open declined to a mean of 14.9 m² by June 2003, which was 116 mo after the burn (Fig. 1). For gaps that

did not burn a second time, the area that remained open declined to < 3 m² by 140 mo after the fire (Fig. 1).

Within gaps, total cover > 0.5 m increased from 1995 (20 mo after the burn) to 2003 (116 mo after the burn; Fig. 2A; Table 3). Cover of scrub oaks, *Serenoa*, woody vines, and native shrubs > 0.5 m increased through that period (Table 4, S1). Cover of native forbs > 0.5 m increased after burning but then declined by the end of the period (Table 4, S1). Total cover < 0.5 m within gaps increased after burning and then declined (Fig. 2B; Table 3), as did native forbs and scrub oaks < 0.5 m (Table 5, S2). Bare ground within gaps declined from 1995 to 2003 (Fig. 2C; Table 5).

Table 3. Estimates and standard errors for the general linear model showing effects of gaps, time since fire, and strata (< 0.5 m and > 0.5 m) on total vegetation cover; > 0.5 m was the base strata. Adjusted R² was 0.6327; P < 0.001. TSF = time since fire. Regression models for each strata are provided in the last rows of the table.

Predictor	Estimate	SE	t	P
Intercept	55.2274	3.01399	18.324	< 0.001
GAP	-49.06451	3.21298	-15.271	< 0.001
LessThan	-19.69996	4.26242	-4.622	< 0.001
TSF	0.73836	0.04674	15.797	< 0.001
GAP:LessThan	74.15088	4.54384	16.319	< 0.001
LessThan:TSF	-1.01643	0.0661	-15.377	< 0.001
Response variable	Scrub matrix		Gap	
< 0.5 cover	35.52744 - 0.27807 × TSF		60.61381 - 0.27807 × TSF	
> 0.5 cover	55.2274 + 0.73836 × TSF		6.16283 + 0.73836 × TSF	

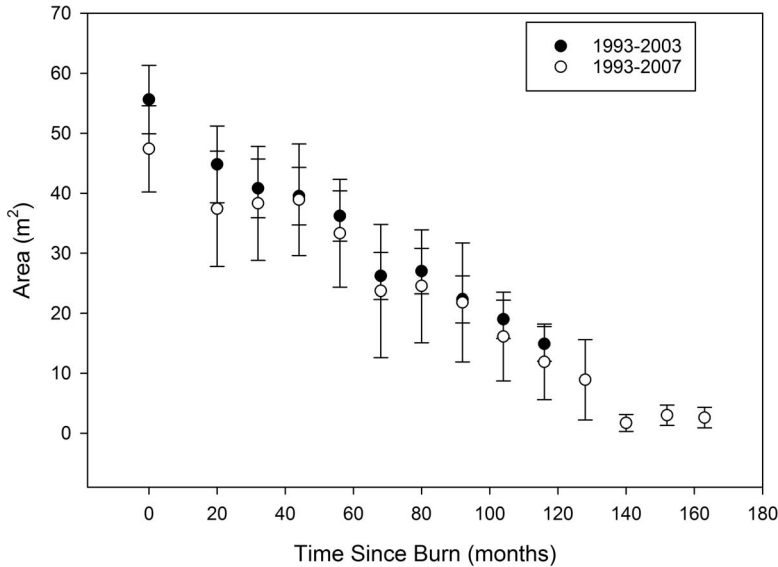


FIG. 1. Change in area of scrub gaps after creation by burn piles. Area of scrub gaps ($N = 12$) from 1993 to 2003 (116 mo after the burn). Area remaining open declined as $\text{Area} = 53.209 - 0.337(\text{time})$, $r = -0.626$, $P < 0.001$. Seven of these gaps burned in 2004. Area of four scrub gaps from 1993 to 2007 (163 mo after the burn). Area remaining open declined as $\text{Area} = 47.782 - 0.304(\text{time})$, $r = -0.70$, $P < 0.001$. These gaps did not burn in 2004. Error bars indicate 1 SE.

In the scrub matrix, total cover > 0.5 m decreased immediately after the burn and then increased (Fig. 2A; Table 3) as did cover > 0.5 m of scrub oaks and *Serenoa* species (Table 4, S5). Woody vines and native shrubs > 0.5 m (Table 4, S5) increased from preburn values after the burn. Native forbs > 0.5 m increased after the burn and then decreased to low values (Table 4, S5). Total cover < 0.5 m in the scrub matrix (Fig. 2B, Table 3) increased after the burn and then declined, as did the cover of scrub oaks and native forbs < 0.5 m (Table 5, S6). Bare ground increased after the burn and then declined (Fig. 2C; Table 5). Native grasses had low cover values > 0.5 m and < 0.5 m in the scrub matrix and gaps (Table 4, 5, S1, S2, S5, S6).

Cover of plant groups differed in the gaps, compared with the scrub matrix, with the exceptions of woody vines > 0.5 m and native shrubs < 0.5 m (Table 4, 5). Gaps had less total cover > 0.5 m (Fig. 2A; Table 3) and less cover of scrub oaks and saw palmetto > 0.5 m. (Table 4, S1, S5). Gaps had greater total cover < 0.5 m than the scrub matrix had (Fig. 2B; Table 3) and greater cover of native forbs < 0.5 m (Table 5, S2, S6) but less cover of scrub oaks < 0.5 m (Table 5, S2, S6). Gaps retained greater bare ground than the scrub matrix (Fig. 2C; Table 5).

No rare or gap-specialist plants established in the gaps (Table S3, S4). Invasive, exotic plants also did not establish and persist in the gaps, with only transitory occurrences of *Melinis repens* (Willd.) Zizka and *Lantana camara* L. (Table S3, S4). Specifically, *Melinis* occurred twice at 20 and 32 mo after the burn at 0.2–0.3% mean cover (Table S3, S4). *Lantana* occurred once at 68 mo after the burn at 0.2% cover (Table S3). In the scrub matrix, *Melinis* occurred at 0.2% or less mean cover at 7, 24, and 30 mo after the burn, but not subsequently, whereas *Lantana* did not occur (P.A.S. and T.E.F., unpublished data).

RESPONSES AFTER SUBSEQUENT BURNS. Seven gaps burned for a second time in May 2004 (Table 1). Gap area increased immediately after the burn to close to the initial size (Fig. 3A). However, gap area declined more rapidly after the second burn than after the original treatment (Fig. 3A). Four gaps burned again in both 2004 and 2008 (Table 1). After both subsequent burns, gap area increased to close to the original size (Fig. 3B). Gap area declined more rapidly after the second and third burns than after the initial treatment, with expected closure at about 5 yr after the burn (Fig 3B). Responses after the second and third burns were similar (Fig. 3B).

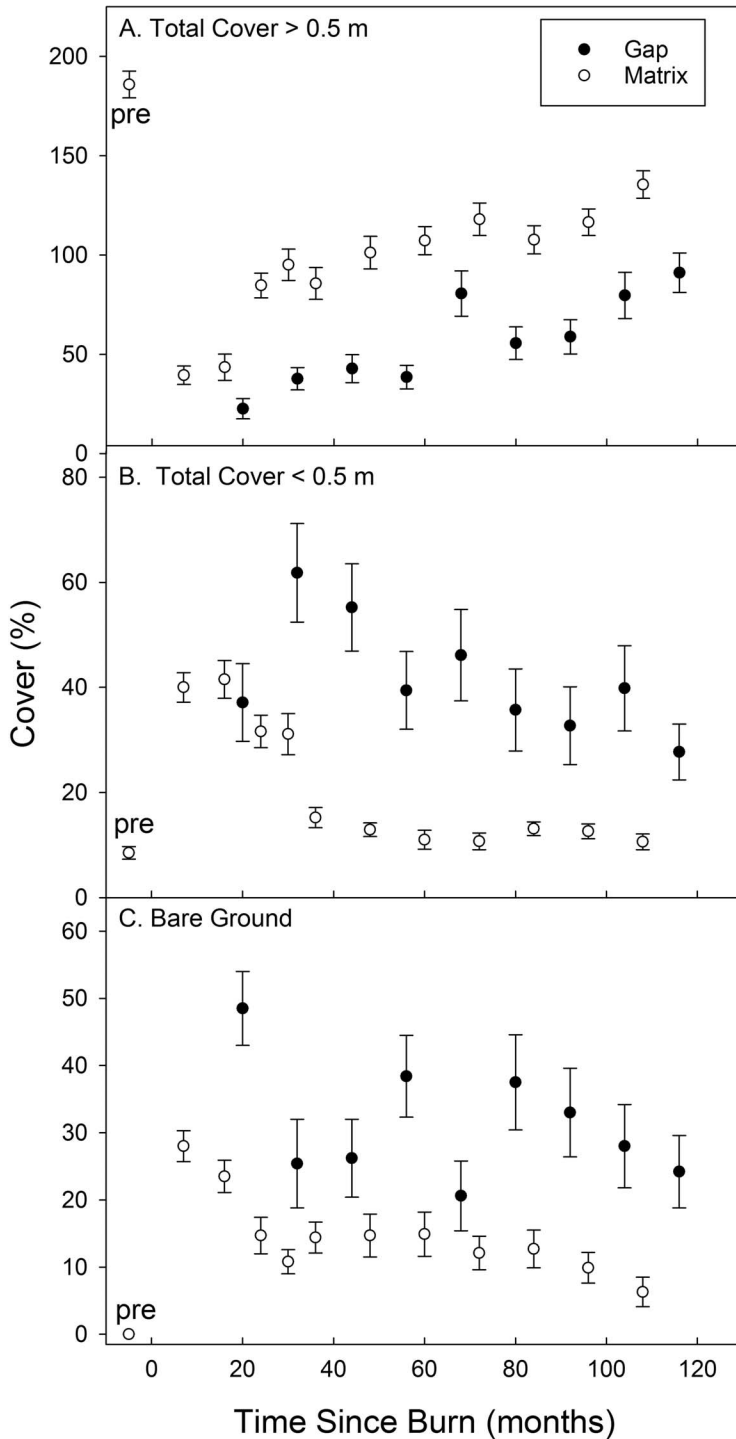


FIG. 2. Comparison of total cover and bare ground in gaps and scrub matrix through 10 yr after the burn. (A) Total cover > 0.5 m in gaps ($N = 12$) created by burning and in the scrub matrix ($N = 20$) from 1993 to 2003. Error bars indicate 1 SE. After the burn, cover differed between gaps and matrix. (B) Total cover < 0.5 m in gaps ($N = 12$) and in the scrub matrix ($N = 20$) created by burning from 1993 to 2003. After the burn, cover differed between gaps and matrix. (C) Bare ground in gaps ($N = 12$) and in the scrub matrix ($N = 20$) created by burning from 1993 to 2003. After the burn, cover differed between gaps and matrix.

Table 4. Estimates and standard errors for the general linear model showing effects of gaps, time since fire, and plant group cover in the > 0.5 m strata. Native Forb is the base plant group. Adjusted R^2 was 0.6491; $P < 0.001$. Plant groups follow Table 2. TSF = time since fire. Regression models for each plant group are provided in the last rows of the table.

Predictor	Estimate	SE	<i>t</i>	<i>P</i>
(Intercept)	5.97747	1.39045	4.299	< 0.001
GAP	5.71374	1.48225	3.855	< 0.001
NatGrass	-4.26575	1.96639	-2.169	0.030
NatShrub	2.60089	1.96639	1.323	0.186
ScrubOak	19.42187	1.96639	9.877	< 0.001
<i>Serenoa</i>	3.75808	1.96639	1.911	0.056
WoodVine	-2.28823	1.96639	-1.164	0.245
TSF	-0.05901	0.02156	-2.737	0.006
GAP:NatGrass	-5.19702	2.09622	-2.479	0.013
GAP:NatShrub	-12.115	2.09622	-5.779	< 0.001
GAP:ScrubOak	-46.8026	2.09622	-22.327	< 0.001
GAP: <i>Serenoa</i>	-13.4831	2.09622	-6.432	< 0.001
GAP:WoodVine	-5.96444	2.09622	-2.845	0.004
NatGrass:TSF	0.04292	0.03049	1.407	0.159
NatShrub:TSF	0.20262	0.03049	6.644	< 0.001
ScrubOak:TSF	0.58384	0.03049	19.146	< 0.001
Serrep:TSF	0.17183	0.03049	5.635	< 0.001
WoodVine:TSF	0.08924	0.03049	2.926	0.003
Response variable	Scrub matrix		Gap	
Native forb cover	5.97747 - 0.059 × TSF		11.69121 - 0.059 × TSF	
Native grass cover	1.71167 - 0.01608 × TSF		2.22841 - 0.01608 × TSF	
Native shrub cover	8.57836 + 0.14362 × TSF		2.1771 + 0.14362 × TSF	
Scrub oak cover	25.39937 + 0.52484 × TSF		-15.6899 + 0.52484 × TSF	
<i>Serenoa</i> cover	9.7355 + 0.11283 × TSF		1.96629 + 0.11283 × TSF	
Woody vine cover	3.68927 + 0.03024 × TSF		3.43861 + 0.03024 × TSF	

Discussion. Burning piled fuels produced gaps in the scrub matrix that persisted for > 10 yr. Increased and longer-duration soil heating appeared to kill the roots and rhizomes of scrub oaks, ericads, and *Serenoa* that resprout under typical fire conditions. These gaps retained greater cover of bare ground and forbs but less cover of scrub oaks and *Serenoa* compared with the scrub matrix. After second and third burns, gap areas initially expanded but closed more rapidly than after the original treatment. This suggests that relatively frequent fire might maintain more gap area. It is also possible that if the second burn had occurred earlier than 10 yr after the original treatment, more of the gap area would have remained open. In rosemary scrub, the gap area declined for 10 yr after the burn but then plateaued in the absence of a second fire (Menges *et al.* 2017). In our study, gap area continued to decline. However, when partially closed gaps burned, the open areas increased in our study, as it did in the rosemary scrub (Menges *et al.* 2017).

Scrub fires are intense stand-replacing fires that typically kill aboveground stems of oaks, ericads,

and *Pinus clausa* (Chapm. ex Engelm.) Vasey ex Sarg. (Myers 1990). The pulse of heat from those fires may exceed 700 °C (Wally *et al.* 2006) but is of short duration. The rapid movement of the flame front and the insulating properties of soil limits heating of the soil (DeBano *et al.* 2005), such that temperatures are not lethal to roots and rhizomes in the soil (Whelan 1995, Busse and DeBano 2005). Alexis *et al.* (2007) found that soil temperatures at 2–3 cm depth remained < 100 °C, litter surface temperatures ranged from 371 to 760 °C, and temperature in the vegetation ranged from 260 to 816 °C in the 2004 prescribed burn of this site.

Scrub oaks have extensive belowground roots and rhizomes (Guerin 1993, Day *et al.* 2013), as do ericads. Belowground biomass of scrub at KSC/MINWR makes up approximately 85% of total biomass (Stover *et al.* 2007). Under normal fire conditions, the belowground roots and rhizomes survive, and after fire, carbon stored belowground is used for sprouting (Stover *et al.* 2007). Sprouting is rapid and scrub vegetation reestablishes cover quickly (Abrahamson 1984a, 1984b, Schmalzer and Hinkle 1992, Schmalzer 2003).

Table 5. Estimates and standard errors for the general linear model showing effects of gaps, time since fire, and plant group cover in the < 0.5 m strata. Bare ground is the base plant group. Adjusted R^2 was 0.5276, $P < 0.001$. Plant groups follow Table 2. TSF = time since fire. Regression models for each plant group are provided in the last rows of the table.

Predictor	Estimate	SE	<i>t</i>	<i>P</i>
(Intercept)	21.63817	1.01927	21.229	< 0.001
GAP	18.58707	1.08656	17.106	< 0.001
NatForb	-12.67067	1.44146	-8.79	< 0.001
NatGrass	-19.54104	1.44146	-13.556	< 0.001
NatShrub	-16.35234	1.44146	-11.344	< 0.001
ScrubOak	-7.00084	1.44146	-4.857	< 0.001
<i>Serenoa</i>	-19.56103	1.44146	-13.57	< 0.001
WoodVine	-20.26708	1.44146	-14.06	< 0.001
TSF	-0.13142	0.01581	-8.314	< 0.001
GAP:NatForb	12.57063	1.53663	8.181	< 0.001
GAP:NatGrass	-16.78667	1.53663	-10.924	< 0.001
GAP:NatShrub	-17.62012	1.53663	-11.467	< 0.001
GAP:ScrubOak	-26.15951	1.53663	-17.024	< 0.001
GAP: <i>Serenoa</i>	-19.67787	1.53663	-12.806	< 0.001
GAP:WoodVine	-18.63449	1.53663	-12.127	< 0.001
NatForb:TSF	0.01671	0.02235	0.747	0.455
NatGrass:TSF	0.11759	0.02235	5.26	< 0.001
NatShrub:TSF	0.09686	0.02235	4.333	< 0.001
ScrubOak:TSF	0.04299	0.02235	1.923	0.055
Serrep:TSF	0.12885	0.02235	5.764	< 0.001
WoodVine:TSF	0.11964	0.02235	5.352	< 0.001
Response Variable	Scrub Matrix		Gap	
Bare ground cover	21.6382 - 0.1314 × TSF		40.2253 - 0.1314 × TSF	
Native forb cover	8.9672 - 0.11469 × TSF		40.1249 - 0.11469 × TSF	
Native grass cover	2.09716 - 0.01381 × TSF		3.89726 - 0.01381 × TSF	
Native shrub cover	5.28496 - 0.03454 × TSF		6.25194 - 0.03454 × TSF	
Scrub oak cover	14.63736 - 0.08841 × TSF		7.06495 - 0.08841 × TSF	
<i>Serenoa</i> cover	2.07717 - 0.00255 × TSF		0.9864 - 0.00255 × TSF	
Woody vine cover	1.37112 - 0.01176 × TSF		1.32373 - 0.01176 × TSF	

Fine roots also recover rapidly after fire (Day *et al.* 2013). Oak cover returns to preburn values usually within 5 yr (Schmalzer 2003). The aboveground buds of *Serenoa* are well-protected, resulting in little fire-related mortality (Abrahamson and Abrahamson 2002). Saw palmetto leaves regenerate rapidly after fire (Abrahamson and Abrahamson 2006), and cover returns to preburn levels usually within 1 yr.

Hence, prescribed burns do not generally lead to the creation of persistent gaps in oak-saw palmetto scrub because of the lack of soil heating. Where logging has produced greater fuels on the ground, residence times of elevated temperatures are longer (Wally *et al.* 2006). Adding fuel elevated the soil temperatures significantly in prescribed burns in flatwoods but did not change shrub regeneration (Hierro and Menges 2002). In maritime chaparral fires, variation in fuel distribution caused spatial variation in surface heating that affected both seed and sprout regeneration (Odion and Davis 2000).

Prolonged heating from burning slash piles or masticated fuels can cause soil heating to depths lethal to soil organisms, plant roots and rhizomes, and seeds (Whelan 1995, Korb *et al.* 2004, Busse *et al.* 2005, DeBano *et al.* 2005). Our data indicate that burning of piled oak stems killed most or all of the roots and rhizomes of oaks, ericads, and *Serenoa* within the pile area, resulting in gaps that persisted for > 10 yr. This differed from the scrub matrix where the percentage bare ground decreased rapidly postfire.

Closure of the gaps that formed was slow, with much of the cover of scrub oaks developing from branches arching over the gap as oaks rooted outside the gap grew in height; this is reflected in the scrub oak cover increasing in > 0.5 m oaks, without first increasing in < 0.5 m scrub oaks, in contrast to the scrub matrix. When subsequent fires top-killed oaks surrounding the gaps, gap area increased. Some clonal spread of oaks, and perhaps *Serenoa*, into gaps was occurring; seedling

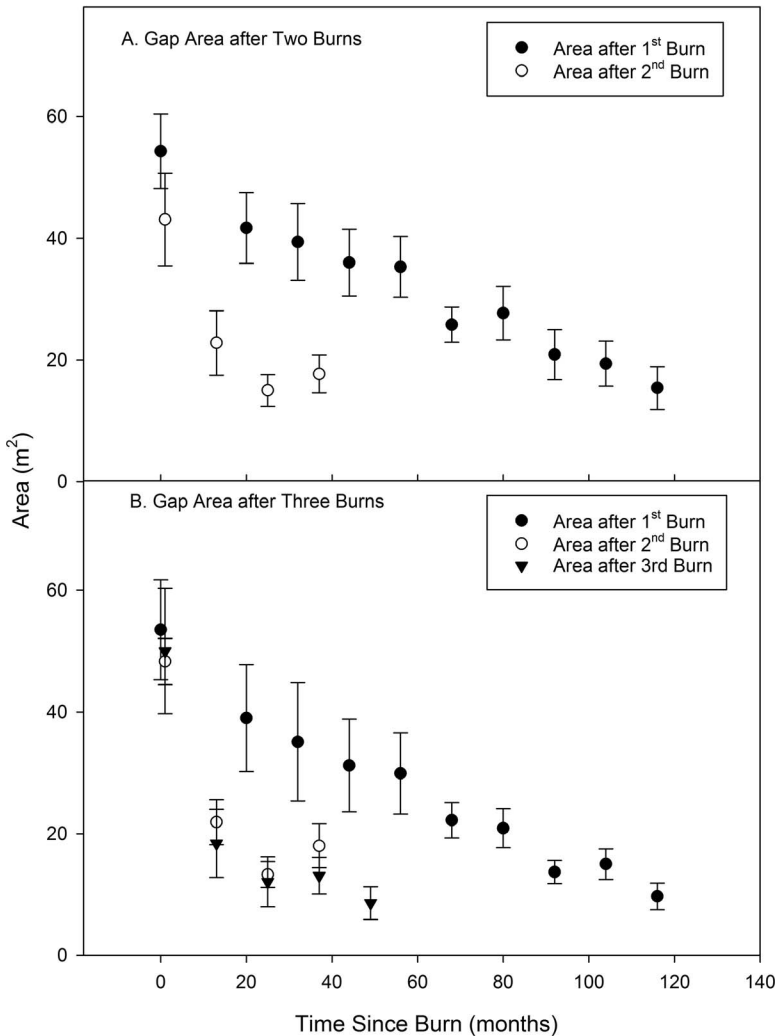


Fig. 3. Changes in area of gaps burned a second and third time. (A) Area of seven gaps created in 1993 and burned again in 2004. Error bars indicate 1 SE. After the first burn, gap area declined as $\text{Area} = 50.624 - 0.311(\text{time})$, $r = -0.678$, $P < 0.001$; after the second burn gap area declined as $\text{Area} = 37.919 - 0.699(\text{time})$, $r = -0.565$, $P = 0.002$. (B) Area of four gaps created in 1993 and burned in 2004 and 2008. After the first burn, gap area declined as $\text{Area} = 48.330 - 0.348(\text{time})$, $r = -0.752$, $P < 0.001$; after the second burn, gap area declined as $\text{Area} = 41.101 - 0.828(\text{time})$, $r = -0.752$, $P = 0.001$; after the third burn, gap area declined as $\text{Area} = 38.805 - 0.734(\text{time})$, $r = -0.686$, $P = 0.001$.

establishment of oaks and *Serenoa* can occur but appears infrequently in the study area. Recovery of belowground biomass is slow compared with the rapid recovery of aboveground biomass by sprouting when the roots and rhizomes remain intact. Other systems that typically recover from disturbance by sprouting show much slower or altered recovery when belowground roots and rhizomes are killed (e.g., Matlack *et al.* 1993, Ehrenfeld *et al.* 1995).

The more-open conditions in the gaps favored herbaceous species. *Galactia elliottii* Nutt. The most abundant herbaceous species in the gaps, also occurs in the surrounding scrub matrix. Whether it established from seed in the soil or dispersed from the adjacent matrix is not known. Invasive, exotic species did not establish persisting populations in the gaps, although old fields with populations of exotic grasses (Schmalzer *et al.* 2002) occurred within < 100 m of some of the gaps.

Gaps in scrub are important for rare scrub plants (Menges and Hawkes 1998, Menges 1999, Menges *et al.* 2008, 2017), but none established in these created gaps. The long period of fire exclusion before restoration began in 1993 probably contributed to the lack of any gap-dependent rare plants in the surrounding scrub matrix. Scrub on KSC/MINWR has fewer rare scrub plants than that of the Lake Wales Ridge (Schmalzer *et al.* 1999), but some gap-dependent scrub plants do occur. Known populations of gap-dependent species, such as *Lechea divaricata* Shuttlw. ex Britton occur approximately 5 km from the study site (Schmalzer and Foster 2016), limiting potential dispersal.

Recovery after burning of slash piles in a restoration project differs from recovery after typical scrub fires, confirming the suggestion of Hierro and Menges (2002) that only very intense fires would alter postfire responses. Are there natural analogs that could produce similar results? Hurricanes or other severe windstorms could produce additional, concentrated fuels that could subsequently burn (Myers and van Lear 1998). Wind and fire may have amplified effects under some circumstances (Cannon *et al.* 2017). Liu *et al.* (2008) presented paleoecological data suggesting that intense hurricanes reduced populations of pines and were followed by intense fires.

The shrub layer of scrub vegetation is relatively resistant to hurricane winds with short-term defoliation and reduction in photosynthesis (Li *et al.* 2007) but little to no damage to rare scrub plants (Menges *et al.* 2011). Of the pines that occur associated with scrub vegetation, *Pinus clausa* is the most vulnerable to hurricane damage that produces debris (Myers 1990, Parker *et al.* 2001, Drewa *et al.* 2008, Menges *et al.* 2011). *Pinus elliotii* Engelm. var. *densa* Little & K.W. Dorman is relatively resistant to hurricane winds (Platt *et al.* 2000), but some damage and mortality does occur. *Pinus palustris* Mill. is also relatively resistant (Provencher *et al.* 2001) but can suffer damage (Kleinman and Hart 2017). We have observed gaps of varying sizes around burned pine stumps, branches, or boles in scrubby flatwoods. Scattered *P. elliotii* var. *densa* occurred in the study site but did not occur on the transects.

There is some potential for hurricanes or similar winds to produce concentrated fuels that, when burned, form gaps. Subsequent, normal fires, if frequent enough, could maintain at least

parts of those gaps by limiting the height and canopy spread of shrubs that would close gaps from the sides because the reestablishment by seed or clonal spread into gaps is slow compared with sprouting from underground rhizomes. This may represent one mechanism by which gaps can form in oak–saw palmetto scrub and scrubby flatwoods that persist for more than a few years after a fire.

Literature Cited

- ABRAHAMSON, W. G. 1984a. Post-fire recovery of Florida Lake Wales Ridge vegetation. *Am. J. Bot.* 71: 9–21.
- ABRAHAMSON, W. G. 1984b. Species responses to fire on the Florida Lake Wales Ridge. *Am. J. Bot.* 71: 35–43.
- ABRAHAMSON, W. G. AND C. R. ABRAHAMSON. 2002. Persistent palmettos: Effects of the 2000–2001 drought on *Serenoa repens* and *Sabal etonia*. *Fla. Sci.* 65: 281–292.
- ABRAHAMSON, W. G. AND C. R. ABRAHAMSON. 2006. Post-fire canopy recovery in two fire-adapted palms, *Serenoa repens* and *Sabal etonia* (Arecaceae). *Fla. Sci.* 69: 69–79.
- ABRAHAMSON, W. G. AND D. C. HARTNETT. 1990. Pine flatwoods and dry prairies, pp. 103–149. *In* R. L. Myers and J. J. Ewel [eds.]. *Ecosystems of Florida*. University of Central Florida Press, Orlando, FL.
- ALEXIS, M. A., D. P. RASSE, C. RUMPEL, G. BARDOUX, N. PECHOT, P. SCHMALZER, B. DRAKE, AND A. MARIOTTI. 2007. Fire impact on C and N losses and charcoal production in a scrub oak ecosystem. *Biogeochemistry* 82: 201–216.
- ANDERSON, K. L. AND D. J. LEOPOLD. 2002. The role of canopy gaps in maintaining vascular plant diversity at a forested wetland in New York State. *J. Torrey Bot. Soc.* 129: 238–250.
- BOND, W. J. AND J. E. KEELEY. 2005. Fire as a global ‘herbivore’: The ecology and evolution of flammable ecosystems. *Trends Ecol. Evol.* 20: 387–394.
- BOND, W. J. AND B. W. VAN WILGEN. 1996. *Fire and Plants*. Chapman & Hall, New York, NY.
- BREININGER, D. R., E. D. STOLEN, G. M. CARTER, D. M. ODDY, AND S. A. LEGARE. 2014. Quantifying how territory quality and sociobiology affect recruitment to inform fire management. *Anim. Conserv.* 17: 72–79.
- BROKAW, N. V. 1985. Treefalls, regrowth, and community structure in tropical forests, pp. 53–69. *In* S. T. A. Pickett and P. S. White [eds.]. *The Ecology of Natural Disturbance and Patch Dynamics*. Academic Press, New York, NY.
- BROKAW, N. AND R. T. BUSING. 2000. Niche versus chance and tree diversity in forest gaps. *Trends Ecol. Evol.* 15: 183–188.
- BUETTEL, J. C., S. ONDEI, AND B. W. BROOK. 2017. Looking down to see what’s up: A systematic overview of treefall dynamics in forests. *Forests* 8: 123. doi: 10.3390/f8040123.
- BUSSE, M. D. AND L. F. DEBANO. 2005. Soil biology, pp. 73–91. *In* D. G. Neary, K. C. Ryan, and L. F. DeBano [eds.]. *Wildland Fire in Ecosystems: Effects of Fire on Soil and Water*. US Department of Agriculture, Forest

- Service, Rocky Mountain Research Station, Ogden, UT. General Technical Report RMRS-GTR-42-volume 4.
- BUSSE, M. D., K. R. HUBBERT, G. O. FIDDLER, C. J. SHESTAK, AND R. F. POWERS. 2005. Lethal soil temperatures during burning of masticated forest residues. *Int. J. Wildland Fire* 14: 267–276.
- CAHILL, J. F., JR. AND B. B. CASPER. 2002. Canopy gaps are sites of reduced belowground competition in a productive old field. *Plant Ecol.* 164: 29–36.
- CANNON, J. B., C. J. PETERSON, J. J. O'BRIEN, AND J. S. BREWER. 2017. A review and classification of interactions between forest disturbance from wind and fire. *For. Ecol. Manag.* 406: 381–390.
- CARREL, J. E. 2003. Burrowing wolf spiders, *Geolycosa* spp. (Araneae: Lycosidae): Gap specialists in fire-maintained Florida scrub. *J. Kans. Entomol. Soc.* 76: 557–566.
- CHRISTMAN, S. P. AND W. S. JUDD. 1990. Notes on plants endemic to Florida scrub. *Fla. Sci.* 53: 52–73.
- CRAWFORD, E. R. AND D. R. YOUNG. 1998. Comparison of gaps and intact shrub thickets on an Atlantic Coast barrier island. *Am. Midl. Nat.* 140: 68–77.
- DAY, F. P., R. E. SCHROEDER, D. B. STOVER, A. L. P. BROWN, J. R. BUTNOR, J. DILUSTRO, B. A. HUNGATE, P. DIJKSTRA, B. D. DUVAL, T. J. SEILER, B. G. DRAKE, AND C. R. HINKLE. 2013. The effects of 11 yr of CO₂ enrichment on roots in a Florida scrub-oak ecosystem. *New Phytol.* 200: 778–787.
- DEBANO, L. F., D. G. NEARY, AND P. F. FFOLIOTT. 2005. Chapter 2: Soil physical properties, pp. 29–51. *In* D. G. Neary, K. C. Ryan, and L. F. DeBano [eds.]. *Wildland Fire in Ecosystems: Effects of Fire on Soil and Water*. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT. General Technical Report RMRS-GTR-42-volume 4.
- DEE, J. R. AND E. S. MENGES. 2014. Gap ecology in the Florida scrubby flatwoods: Effects of time-since-fire, gap area, gap aggregation and microhabitat on gap species diversity. *J. Veg. Sci.* 25: 1235–1246.
- DENSLOW, J. S. AND T. SPIES. 1990. Canopy gaps in forest ecosystems: An introduction. *Can. J. For. Res.* 20: 619.
- DICKINSON, M. B., F. E. PUTZ, AND C. D. CANHAM. 1993. Canopy gap closure in thickets of the clonal shrub, *Cornus racemosa*. *Bull. Torrey Bot. Club* 120: 439–444.
- DIRZO, R. C., C. HORVITZ, H. QUEVEDO, AND M. A. LOPEZ. 1992. The effects of gap size and age on the understory herb community of a tropical Mexican rainforest. *J. Ecol.* 80: 809–822.
- DREWA, P. B., W. J. PLATT, C. KWIT, AND T. W. DOYLE. 2008. Stand structure and dynamics of sand pine differ between the Florida panhandle and peninsula. *Plant Ecol.* 196: 15–25.
- DUNCAN, B. W., S. BOYLE, D. R. BREININGER, AND P. A. SCHMALZER. 1999. Coupling past management practice and historic landscape change on John F. Kennedy Space Center. *Landsc. Ecol.* 14: 291–309.
- EHRENFELD, J. G., W. ZHU, AND W. F. J. PARSONS. 1995. Above- and below-ground characteristics of persistent forest openings in the New Jersey Pinelands. *Bull. Torrey Bot. Club* 122: 298–305.
- FRANZESE, J., L. GHERMANDI, AND D. BRAN. 2009. Post-fire recruitment in a semi-arid grassland: The role of microsites. *J. Veg. Sci.* 20: 251–259.
- GARDNER, R. H. AND K. A. M. ENGELHARDT. 2008. Spatial processes that maintain biodiversity in plant communities. *Perspect. Plant Ecol. Evol. Syst.* 9: 211–228.
- GREENBERG, C. H., D. G. NEARY, AND L. D. HARRIS. 1994. Effects of high-intensity wildfire and silvicultural treatments on reptile communities in sand pine scrub. *Conserv. Biol.* 8: 1047–1057.
- GUERIN, D. N. 1993. Oak dome clonal structure and fire ecology in a Florida longleaf pine dominated community. *Bull. Torrey Bot. Club* 120: 107–114.
- HAWKES, C. V. AND E. S. MENGES. 1996. The relationship between open space and fire for species in a xeric Florida shrubland. *Bull. Torrey Bot. Club* 123: 81–92.
- HEWITT, R. E. AND E. S. MENGES. 2008. Allelopathic effects of *Ceratiola ericoides* (Empetraceae) on germination and survival of six Florida scrub species. *Plant Ecol.* 198: 47–59.
- HIERRO, J. L. AND E. S. MENGES. 2002. Fire intensity and shrub regeneration in palmetto-dominated flatwoods of central Florida. *Fla. Sci.* 65: 51–61.
- HOKIT, D. G., B. M. STITH, AND L. C. BRANCH. 1999. Effects of landscape structure in Florida scrub: A population perspective. *Ecol. Appl.* 9: 124–134.
- HUCKLE, H. F., H. D. DOLLAR, AND R. F. PENDLETON. 1974. Soil survey of Brevard County, Florida. US Department of Agriculture, Soil Conservation Service, Washington, DC.
- HUNTER, M. E. AND E. S. MENGES. 2002. Allelopathic effects and root distribution of *Ceratiola ericoides* (Empetraceae) on seven rosemary scrub species. *Am. J. Bot.* 89: 1113–1118.
- JOHNSON, A. F. 1982. Some demographic characteristics of the Florida rosemary *Ceratiola ericoides* Michx. *Am. Midl. Nat.* 108: 170–174.
- KEELEY, J. E., V. T. PARKER, AND M. C. VASEY. 2016. Resprouting and seeding hypotheses: A test of the gap-dependent model using resprouting and obligate seeding subspecies of *Arctostaphylos*. *Plant Ecol.* 217: 743–750.
- KLEINMAN, J. S. AND J. L. HART. 2017. Response by vertical strata to catastrophic wind in restored *Pinus palustris* stands. *J. Torrey Bot. Soc.* 144: 423–438.
- KORB, J. E., N. C. JOHNSON, AND W. W. COVINGTON. 2004. Slash pile burning effects on soil biotic and chemical properties and plant establishment: Recommendations for amelioration. *Restor. Ecol.* 12: 52–62.
- KWIT, C. AND W. J. PLATT. 2003. Disturbance history influences regeneration of non-pioneer understory trees. *Ecology* 84: 2575–2581.
- LI, J. H., T. L. POWELL, T. J. SEILER, D. P. JOHNSON, H. P. ANDERSON, R. BRACHO, B. A. HUNGATE, C. R. HINKLE, AND B. G. DRAKE. 2007. Impacts of Hurricane Frances on Florida scrub-oak ecosystem processes: Defoliation, net CO₂ exchange and interactions with elevated CO₂. *Glob. Change Biol.* 13: 1101–1113.
- LIU, K.-B., H. LU, AND C. SHEN. 2008. A 1200-year proxy record of hurricanes and fires from the Gulf of Mexico coast: Testing the hypothesis of hurricane-fire interactions. *Quat. Res. (Orlando)* 69: 29–41.

- MARTINS, S. V. AND R. R. RODRIGUES. 2002. Gap-phase regeneration in a semideciduous mesophytic forest, south-eastern Brazil. *Plant Ecol.* 163: 51–62.
- MATLACK, G. R., D. J. GIBSON, AND R. E. GOOD. 1993. Clonal propagation, local disturbance, and the structure of vegetation: Ericaceous shrubs in the Pine Barrens of New Jersey. *Biol. Conserv.* 63: 1–8.
- MCCARTHY, J. 2001. Gap dynamics of forest trees: A review with particular attention to boreal forests. *Environ. Rev.* 9: 1–59.
- MCGUIRE, J. P., R. J. MITCHELL, E. B. MOSER, S. D. PECOT, D. H. GJERSTAD, AND C. W. HEDMAN. 2001. Gaps in a gappy forest: Plant resources, longleaf pine regeneration, and understory response to tree removal in longleaf pine savannas. *Can. J. For. Res.* 31: 765–778.
- MENGES, E. S. 1999. Ecology and conservation of Florida scrub, pp. 7–22. *In* R. C. Anderson, J. S. Fralish, and J. M. Baskin [eds.]. *Savannas, Barrens and Rock Outcrop Plant Communities of North America*. Cambridge University Press, New York, NY.
- MENGES, E. S. AND C. V. HAWKES. 1998. Interactive effects of fire and microhabitat on plants of Florida scrub. *Ecol. Appl.* 8: 935–946.
- MENGES, E. S., S. J. H. CRATE, AND P. F. QUINTANA-ASCENCIO. 2017. Dynamics of gaps, vegetation, and plant species with and without fire. *Am. J. Bot.* 104: 1825–1836.
- MENGES, E. S., C. W. WEEKLEY, G. L. CLARKE, AND S. A. SMITH. 2011. Effects of hurricanes on rare plant demography in fire-controlled ecosystems. *Biotropica* 43: 450–458.
- MENGES, E. S., A. CRADDOCK, J. SALO, R. ZINTHEFER, AND C. W. WEEKLEY. 2008. Gap ecology in Florida scrub: Species occurrence, diversity, and gap properties. *J. Veg. Sci.* 19: 503–514.
- MITCHELL, R. J., J. K. HIERS, J. O'BRIEN, AND G. STARR. 2009. Ecological forestry in the Southeast: Understanding the ecology of fuels. *J. Forestry* 107: 391–397.
- MITCHELL, S. J. 2013. Wind as a natural disturbance agent in forests: A synthesis. *Forestry* 86: 147–157.
- MUELLER-DOMBOIS, D. AND H. ELLENBERG. 1974. *Aims and methods of vegetation ecology*. John Wiley & Sons, New York, NY.
- MUSCOLO, A., S. BAGNATO AND R. MERCURIO. 2014. A review of the roles of forest canopy gaps. *J. For. Res.* 25: 725–746.
- MYERS, R. K. AND D. H. VAN LEAR. 1998. Hurricane-fire interactions in coastal forest of the south: A review and hypothesis. *For. Ecol. Manag.* 103: 265–276.
- MYERS, R. L. 1990. Scrub and high pine, pp. 150–193. *In* R. L. Myers and J. J. Ewell [eds.]. *Ecosystems of Florida*. University of Central Florida Press, Orlando, FL.
- NAGEL, T. A., S. MIKAC, M. DOLINAR, M. KLOPIC, S. KEREN, M. SVOBODA, J. DIACI, A. BONCINA, AND V. PAULIC. 2017. The natural disturbance regime in forests of the Dinaric Mountains: A synthesis of evidence. *For. Ecol. Manag.* 388: 29–42.
- O'BRIEN, J. J., E. L. LOUDERMILK, B. HORNSBY, A. T. HUDAK, B. C. BRIGHT, M. B. DICKINSON, J. K. HIERS, C. TESKE, AND R. D. OTTMAR. 2016. High-resolution infrared thermography for capturing wildland fire behavior—RxCADRE 2012. *Int. J. Wildland Fire* 25: 62–75.
- ODION, D. C. AND F. W. DAVIS. 2000. Fire, soil heating, and the formation of vegetation patterns in chaparral. *Ecol. Monogr.* 70: 149–169.
- PARKER, A. J., K. C. PARKER, AND D. H. McCAY. 2001. Disturbance-mediated variation in stand structure between varieties of *Pinus clausa* (sand pine). *Ann. Assoc. Am. Geogr.* 91: 28–47.
- PECOT, S. D., R. J. MITCHELL, B. J. PALIK, E. B. MOSER, AND J. K. HIERS. 2007. Competitive responses of seedlings and understory plants in longleaf pine woodlands: Separating canopy influences above and below ground. *Can. J. For. Res.* 37: 634–648.
- PICKETT, S. T. A. AND P. S. WHITE [EDS.]. 1985. *The Ecology of Natural Disturbance and Patch Dynamics*. Academic Press, New York, NY.
- PLATT, W. J. AND D. R. STRONG. 1989. Special feature: Gaps in forest ecology. *Ecology* 70: 535.
- PLATT, W. J. AND I. M. WEIS. 1977. Resource partitioning and competition within a guild of fugitive prairie plants. *Am. Nat.* 111: 479–513.
- PLATT, W. J., R. F. DOREN, AND T. V. ARMENTANO. 2000. Effects of Hurricane Andrew on stands of slash pine (*Pinus elliottii* var. *densa*) in the Everglades region of south Florida (USA). *Plant Ecol.* 146: 43–60.
- PROVENCHER, L., A. R. LITT, D. R. GORDON, H. L. RODGERS, B. J. HERRING, K. E. M. GALLEY, J. P. McADOO, S. J. McADOO, N. M. GOBRIS, AND J. L. HARDESTY. 2001. Restoration fire and hurricanes in longleaf pine sandhills. *Ecol. Restor.* 19: 92–98.
- RANTIS, P.-A. AND J. E. JOHNSON. 2002. Understory development in canopy gaps of pine and pine-hardwood forests of the upper Coastal Plain of Virginia. *Plant Ecol.* 159: 103–115.
- REBERTUS, A. J. AND B. R. BURNS. 1997. The importance of gap processes in the development and maintenance of oak savannas and dry forests. *J. Ecol.* 85: 635–645.
- RUNKLE, J. R. 1985. Disturbance regimes in temperate forests, pp. 17–33. *In* S. T. A. Pickett and P. S. White [eds.]. *The Ecology of Natural Disturbance and Patch Dynamics*. Academic Press, New York, NY.
- RUNKLE, J. R. 1992. *Guidelines and Sample Protocol for Sampling Forest Gaps*. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. General Technical Report PNW-GTR-283.
- RUNKLE, J. R. 1998. Changes in southern Appalachian canopy tree gaps sample thrice. *Ecology* 79: 1768–1780.
- SCHLIEMANN, S. A., AND J. G. BROCKHEIM. 2011. Methods for studying treefall gaps. *For. Ecol. Manag.* 261: 1143–1151.
- SCHMALZER, P. A. 2003. Growth and recovery of oak-saw palmetto scrub through ten years after fire. *Nat. Areas J.* 23: 5–13.
- SCHMALZER, P. A. AND T. E. FOSTER. 2016. Flora and threatened and endangered plants of Canaveral National Seashore, Florida. *Castanea* 81: 91–127.
- SCHMALZER, P. A. AND C. R. HINKLE. 1992. Recovery of oak-saw palmetto after fire. *Castanea* 57: 158–173.

- SCHMALZER, P. A., S. R. BOYLE, AND H. M. SWAIN. 1999. Scrub ecosystems of Brevard County, Florida: A regional characterization. *Fla. Sci.* 62: 13–47.
- SCHMALZER, P. A., D. R. BREININGER, F. ADRIAN, R. SCHAUB, AND B. W. DUNCAN. 1994. Development and implementation of a scrub habitat compensation plan for Kennedy Space Center. Kennedy Space Center, FL. NASA Technical Memorandum 109202.
- SCHMALZER, P. A., S. R. TUREK, T. E. FOSTER, C. A. DUNLEVY, AND F. W. ADRIAN. 2002. Reestablishing Florida scrub in a former agricultural site: Survival and growth of planted species and changes in community composition. *Castanea* 67: 146–160.
- SPIES, T. A., J. F. FRANKLIN, AND M. KLOPSCH. 1990. Canopy gaps in Douglas-fir forests of the Cascade Mountains. *Can. J. For. Res.* 20: 649–658.
- STOUT, I. J. 2001. Rare plants of the Florida scrub. *Nat. Areas J.* 21: 50–60.
- STOVER, D. B., F. P. DAY, J. R. BUTNOR, AND B. G. DRAKE. 2007. Effect of elevated CO₂ on coarse-root biomass in Florida scrub detected by ground-penetrating radar. *Ecology* 88: 1328–1334.
- THAXTON, J. M. AND W. J. PLATT. 2006. Small-scale fuel variation alters fire intensity and shrub abundance in a pine savanna. *Ecology* 87: 1331–1337.
- TOZER, K. N., D. F. CHAPMAN, P. E. QUIGLEY, P. M. DOWLING, R. D. COUSENS, G. A. KEARNEY, AND J. R. SEDCOLE. 2008. Controlling invasive annual grasses in grazed pastures: Population dynamics and critical gap sizes. *J. Appl. Ecol.* 45: 1152–1159.
- TURNER, M. G., W. H. ROMME, AND D. B. TINKER. 2003. Surprises and lessons from the 1988 Yellowstone fires. *Front. Ecol. Environ.* 1: 351–358.
- TURNER, M. G., W. W. HARGROVE, R. H. GARDNER, AND W. H. ROMME. 1994. Effects of fire on landscape heterogeneity in Yellowstone National Park, Wyoming. *J. Veg. Sci.* 5: 731–742.
- WALLY, A. L., E. S. MENGES, AND C. W. WEEKLEY. 2006. Comparison of three devices for estimating fire temperatures in ecological studies. *Appl. Veg. Sci.* 9: 97–108.
- WATT, A. S. 1947. Pattern and process in the plant community. *J. Ecol.* 35: 1–22.
- WEEKLEY, C. W., D. GAGNON, E. S. MENGES, P. F. QUINTANA-ASCENCIO, AND S. SAHA. 2007. Variation in soil moisture in relation to rainfall, vegetation, gaps, and time-since-fire in Florida scrub. *Ecoscience* 14: 377–386.
- WHELAN, R. J. 1995. *The Ecology of Fire*. Cambridge University Press, Cambridge, UK.
- WHITE, P. S. 1979. Pattern, process, and natural disturbance in vegetation. *Bot. Rev.* 45: 229–299.
- WILLIAMS, R. J. 1992. Gaps in subalpine heathland and grassland vegetation in south-eastern Australia. *J. Ecol.* 80: 343–352.
- WUNDERLIN, R. P. AND B. F. HANSEN. 2011. *Guide to the Vascular Plants of Florida*, 3rd ed. University Presses of Florida, Gainesville, FL.
- YAMAMOTO, S.-I. 1992. The gap theory in forest dynamics. *J. Plant Res.* 105: 375–383.
- YAO, A. W., J. M. CHIANG, R. MCEWAN, AND T. C. LIN. 2015. The effect of typhoon-related defoliation on the ecology of gap dynamics in a subtropical forest of Taiwan. *J. Veg. Sci.* 26: 145–154.
- YOUNG, C. C. AND E. S. MENGES. 1999. Postfire gap-phase regeneration in scrubby flatwoods on the Lake Wales Ridge. *Fla. Sci.* 62: 1–12.
- ZHU, J., D. LU AND W. ZHANG. 2014. Effects of gaps on regeneration of woody plants: A meta-analysis. *J. For. Res.* 25: 501–510.