RESEARCH ARTICLE

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Effects of Fire Intensity on Vital Rates of an Endemic Herb of the Florida Keys, USA

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ABSTRACT: Fire intensity is one of the important components of a fire regime. However, relatively few studies have linked fire intensity with post-fire population vital rates. In this study, we explored the effects of fire intensity on population vital rates of *Chamaecrista keyensis* Pennell (Fabaceae) up to two years post-fire. *C. keyensis* is an endemic understory plant of pine rockland, a fire-dependent ecosystem of the Lower Florida Keys. We measured one fire intensity indicator, fire temperature reached by steel plates on the ground, during three prescribed fires at different sites. We followed marked individuals up to two years post-fire to derive annual survival, annual growth rate, percentage of fruiting plants, mean number of fruits per reproductive plant, and number of seedlings per census plot (1 m^2) of *C. keyensis*. We found fire intensity had significant effects on reproduction in the first year post-fire only. More specifically, mean number of fruits and percentage of fruiting plants increased as fire intensity increased. Results from this study suggest that extremely low fire intensity caused by very short fire return intervals (e.g., less than three years) may not provide sufficient stimulation to reproduction to achieve the best post-fire recovery for *C. keyensis*.

Index terms: Chamaecrista keyensis, fire intensity, fire temperature, pine rockland, rare plant demography

INTRODUCTION

Fire intensity, defined as the heat release per unit time (Rothermel 1972, Pyne et al. 1996), differs not only among fires of different ecosystems, but within the same ecosystem, and is also heterogeneous within a single fire. Several studies have shown that fire intensity is an important factor shaping fire-dependent community composition and structure, and population dynamics (Moreno and Oechel 1991, Tyler 1995, Ansley et al. 1998, Odion and Davis 2000, Menges and Deyrup 2001, Brooks 2002). Most fire intensity studies have focused on only one or two demographic parameters (e.g., mortality or seedling recruitment) immediately after fire. Studies of effects of fire intensity on multiple population vital rates over a longer time period are truly rare.

The Florida pine rockland is a globally endangered fire dependent ecosystem (Snyder et al. 1990). Fire return interval is a major factor influencing pine rockland community structure and composition (Snyder et al. 1990, Slocum et al. 2003). The seasonal timing of fire is also thought to be important in this ecosystem, and has been shown to influence demography of pine rockland plant populations (Spier and Snyder 1998, Negrón-Ortiz and Gorchov 2000). The role of fire intensity in determining post-fire population dynamics, however, is largely unknown in pine rockland.

Fire intensity, in the strict sense, is difficult to measure in the field. As a result, it is commonly estimated via several surrogate variables that are relatively easy to obtain in the field, including maximum surface temperature (e.g., Negrón-Ortiz and Gorchov 2000), minimum diameter of remaining branches (e.g., Moreno and Oechel 1991), water evaporative loss (e.g., Moreno and Oechel 1991), char height (Menges and Deyrup 2001), and fuel consumption (Pyne et al. 1996). In this study, we used fire temperature reached by steel plates on the ground as the fire intensity indicator. We studied the effects of fire intensity on mortality, growth, reproduction, and seedling recruitment of *Chamaecrista keyensis* Pennell (Fabaceae), a narrowly endemic understory herb of pine rockland of the Lower Florida Keys.

MATERIAL AND METHODS

Study species

Chamaecrista keyensis, commonly known as Big Pine partridge pea, was formerly found on several of the Lower Keys (No Name, Big Pine, and Ramrod Keys [Irwin and Barneby 1982]). More recently, Ross and Ruiz (1996) found it only on Big Pine Key, indicating its probable extirpation from parts of its former range. The most prominent threats to this species include habitat loss and degradation, especially long-term fire exclusion (Snyder et al. 1990). *C. keyensis* has been recommended for federal listing and is currently listed as an endangered species by the State of Florida (Florida Natural Areas Inventory, 2002). *C. keyensis* individuals suffer relatively high mortality rates during fires. Post-fire recovery relies on vegetative resprouting from surviving individuals and seedling recruitment from the seed bank and seeds produced post-fire (Liu et al., in press).

Study site

Pine rockland on Big Pine Key, the only island currently supporting *C. keyensis*, is also an important habitat for the federally endangered key deer (*Odocoilcus virginianus clavium* Barbour and Allen). The canopy of pine rocklands is monotypic, composed of South Florida slash pine (*Pinus elliottii* var. *densa*). The relatively open canopy allows the growth of a diverse shrub and herb layer with many rare and endemic species (Snyder et al. 1990).

Pinelands on Big Pine Key are a mosaic of open and shrubby pinelands, created by a sporadic regime of prescribed burns (Bergh and Wisby 1996). Fire history and site factors both contribute to the distinction between these cover types; in the absence of fire for extended periods, open forests on Big Pine Key become shrub-dominated. The open pinelands have a relatively sparse shrub layer and a well-developed herb layer. In contrast, shrubby pinelands have a dense shrub layer and poorly developed herb layer.

Chamaecrista keyensis census and fire intensity measurements

This study was part of a larger effort investigating effects of different fire regimes, including fire season, on pine rockland vegetation. We generated seven prescribed burns during the summer or winter seasons on experimental blocks of open or shrubby pinelands (Liu 2003). Here we used data from three experimental burns that had good fire intensity measurements (Table 1). Among the three burned sites, two (IS and IW) were on open pineland, while one (DW) was on shrubby pineland. One macro-plot (1 ha) was embedded in each experimental burn site of 2-10 ha. Within each macro-plot, 20 shrub plots (4 m in diameter) were located stratified-randomly, with four herb plots (1 m^2) nested within each shrub plot. *C. keyensis* censuses were carried out in the herb plots. Additional non-random census plots were established to include more individuals of *C. keyensis* for sampling (Table 1). We mapped all *C. keyensis* in each census plot, and measured the stem length and the number of stems, flowers, and fruits of each individual once before and annually for up to two years after each fire.

Fire temperatures were recorded during the three fires using 10 temperature-sensitive paints, each of which melted at a particular temperature from 93°C to 343°C at 28°C intervals. Steel plates (75 mm x 75 mm x 3 mm, 128 g) painted with small dots of the temperature-sensitive paints were placed vertically just aboveground at the center of each census plot before each fire. The plates were recovered immediately after the fire, and maximum fire temperature at each census plot was assigned to the highest temperature reached as indicated by melting. Plates where no melting was observed were arbitrarily assigned a value of 38°C.

Chamaecrista keyensis demographic vital rates derived from individual plants were averaged for each census plot to match the scale of maximum fire temperature measurements. Variables included annual percent survival, mean annual growth (current total stem length / previous year total stem length), percent reproductive plants, mean number of fruits per reproductive plant, and presence/absence and number of seedlings. Annual survival and growth included the period from the summer before to the summer after fire (one year post-burn), as well as annual survival and growth for the subsequent year (two-year post-burn). Percentage of reproductive plants, mean fruit production, and seedling recruitment were summarized for the first and second year post-fire. Only one year post-burn data were available for macroplot IW (Table 1).

Statistical analyses

Differences in maximum fire temperatures among sites was analyzed with one-way ANOVA followed by Tukey post hoc tests. Effects of maximum fire temperature on vital rates were performed separately for each vital rate and each year. Analysis of Covariance (ANCOVA) was used to test the effects of site and fire temperature (covariate) on all vital rates of *C. keyensis* except for presence/absence of seedlings. Presence/absence of seedlings was analyzed with binary logistic regression using maximum fire temperature as a covariate and site and previous fruit production as factors. Some variables were transformed to satisfy the parametric assumptions of normality and equal variance.

In addition, the ANCOVA assumption of parallel slopes of the covariate among sites was satisfied, as indicated by the non-significant interactions between fire temperature and site or previous year fruit production (for seedling-related variables only). Since there were census plots with no melted paint, an indication that those plots were lightly burned or not burned, we

Table 1. Summary of *Chamaecrista keyensis* census regime for fire intensity research. Chamaecrista keyensis density is based on stratified random plots only.

Site	Density /m^2	# of census plots[1]	Census period	Burn Date
IS	1.03	95	1999-2001	July 14, 1999
IW	0.27	105	2000-2001	December 12, 2000
DS	0.47	105	1999-2001	June 22, 1999

[1] 80 of these plots were stratified random plots, others were non-random census plots.

also repeated our analysis excluding these census plots to see if the results changed qualitatively. Differences in vital rates in burned vs. unburned plots were analyzed elsewhere.

RESULTS

The highest and lowest fire temperatures reached by all three burns were 343°C and 38°C, respectively. The mean fire temperature was different significantly among the three sites ($F_{2, 292} = 20.09$, $P < 0.001$; Figure 1) and between each pair of sites (Figure 1).

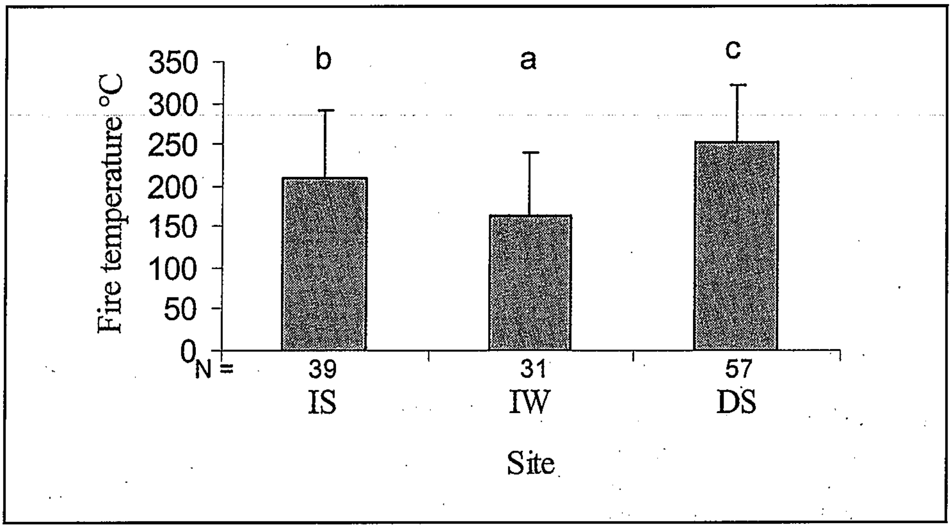

Figure 1. Mean and standard deviation of maximum fire temperature at three sites. Different letters indicate significant differences among sites (Tukey post hoc) at P < 0.05.

Survival differed significantly among sites, but was not affected by fire temperature during the first or second year post-fire (Table 2). Similarly, fire temperature had no significant effects on growth during those years (Table 2). Site had a significant effect on growth one-year post-fire, but not the second year post-fire (Table 2).

In contrast, fire temperature had a significant effect on percentage of fruiting individuals during the first year post-fire (Figure 2), but not the second year post-fire (Table 2). Site effects were significant both one- and two-years post-burn (Table 2). Similarly, fire temperature had significant effects on the mean number of fruits one-year post-fire (Table 2, Figure 3), but not during the subsequent year (Table 2). Site effects were significant both one- and two-years post-fire (Table 2).

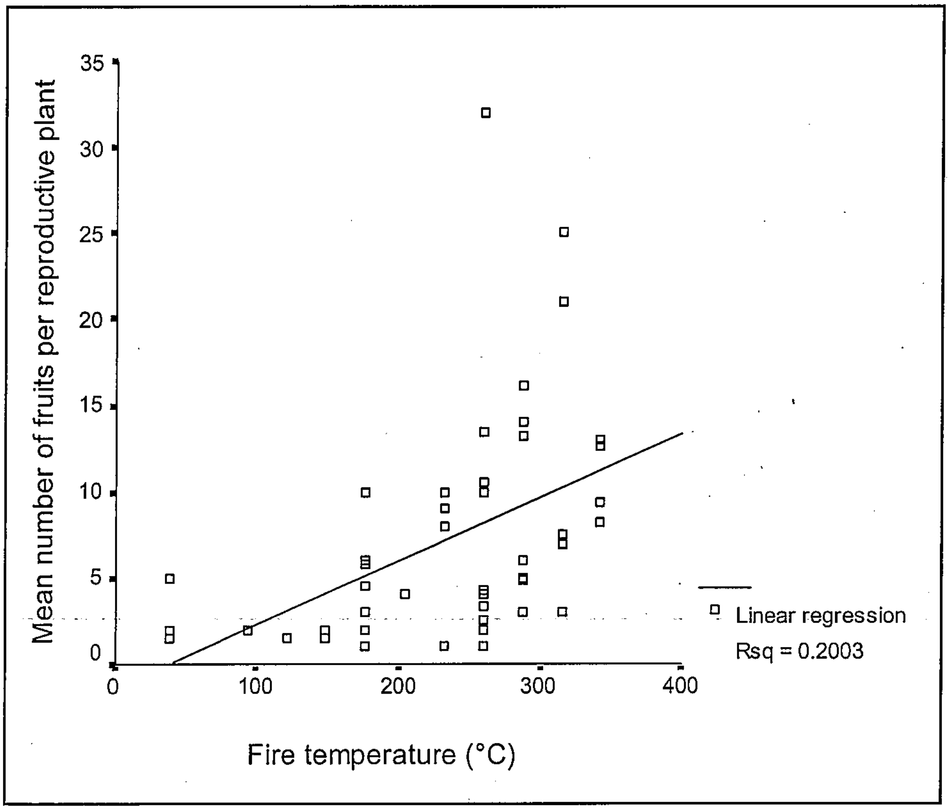

Figure 2. Scatterplot of percentage of fruiting plants (non-seedlings only) of *Chamaecrista keyensis* on Big Pine Key the first year post-fire vs. maximum fire intensity.

Fire temperature, site, and/or the interaction between site and fruit production the previous year had no significant effects on presence or absence of seedlings (Table 3). Previous year's fruit production, however, had a marginally positive effect on seedling presence (Table 3).

Fire temperature had no significant effect on the number of seedlings either one or two years post-fire (Table 2). In addition, previous fruit production, as well as the interaction of site and fruit production the previous year, was not significant in either year (Tables 2). In contrast, site effects were significant the first year post-fire but not the second year post-fire (Table 2).

DISCUSSION

Effects of fire intensity

Effects of fire intensity were found only on the reproduction of *Chamaecrista keyensis* the first year post-fire, but not on its survival, growth, or seedling recruitment. While numerous studies have documented increased flowering in response to fire (e.g., Spier and Snyder 1998, Carrington 1999), few, if any, have linked increased reproduction to fire intensity. However,

Table 2. Effects of maximum fire temperature on *Chamaecrista keyensis* vital rates: summary of ANCOVA including all plots including those with no melted paint. Bold indicates P < 0.05 level. Italic indicates P < 0.1 level. Shaded area indicates non- applicable tests. Fire temp = fire temperature; Pyf = previous year fruit production.

Year post fire	Factor	Vital rate								
		Annual survival			Annual growth			Percent of fruiting plant		
		MS	$F_{df1,df2}$	*P*	MS	$F_{df1,df2}$	*P*	MS	$F_{df1,df2}$	*P*
Year 1	Fire temp	1450	$1.38_{1,106}$	0.243	0.06	$0.12_{1,81}$	0.725	4047	$5.84_{1,87}$	**0.018**
	site	17040	$8.12_{2,106}$	**0.001**	17.8	$35.9_{2,81}$	**0**	31953	$46.1_{2,87}$	**0**
	Pyf	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Site* Pyf	▨	▨	▨	▨	▨	▨	▨	▨	▨
Year 2	Fire temp	0.17	$0.75_{1,74}$	0.388	1.32	$2.14_{1,65}$	0.148	0.52	$2.17_{1,70}$	0.145
	site	2.51	$11.17_{1,74}$	**0.001**	0.03	$0.04_{1,65}$	0.84	2.99	$12.5_{1,70}$	**0.001**
	Pyf	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Site* Pyf	▨	▨	▨	▨	▨	▨	▨	▨	▨

Spier and Snyder (1998) did observe that the number of flowers and fruits of *Jacquemontia curtisii* were significantly greater after cooler fires. They attributed such differences in reproduction to the difference in season of burning, rather than fire intensity effects. The significant effects of fire intensity on *C. keyensis* reproduction (both percentage of fruiting plants and mean number of fruits) were in part due to inclusion of census plots that were either lightly burned or not burned, as such effects became non-significant or marginally significant when these plots were excluded (Liu 2003). Plants in census plots lightly burned or unburned (but in the burned area) did not reproduce as much as plants in census plots more thoroughly burned. Nevertheless, the trends of positive effects of fire intensity on *C. keyensis* reproduction were similar with or without these plots. Perhaps nutrient availability was greater or aboveground competitions were less in more intensely burned sites, thereby stimulating reproduction. The mechanism of fire intensity's effect on reproduction is unclear and needs further investigation.

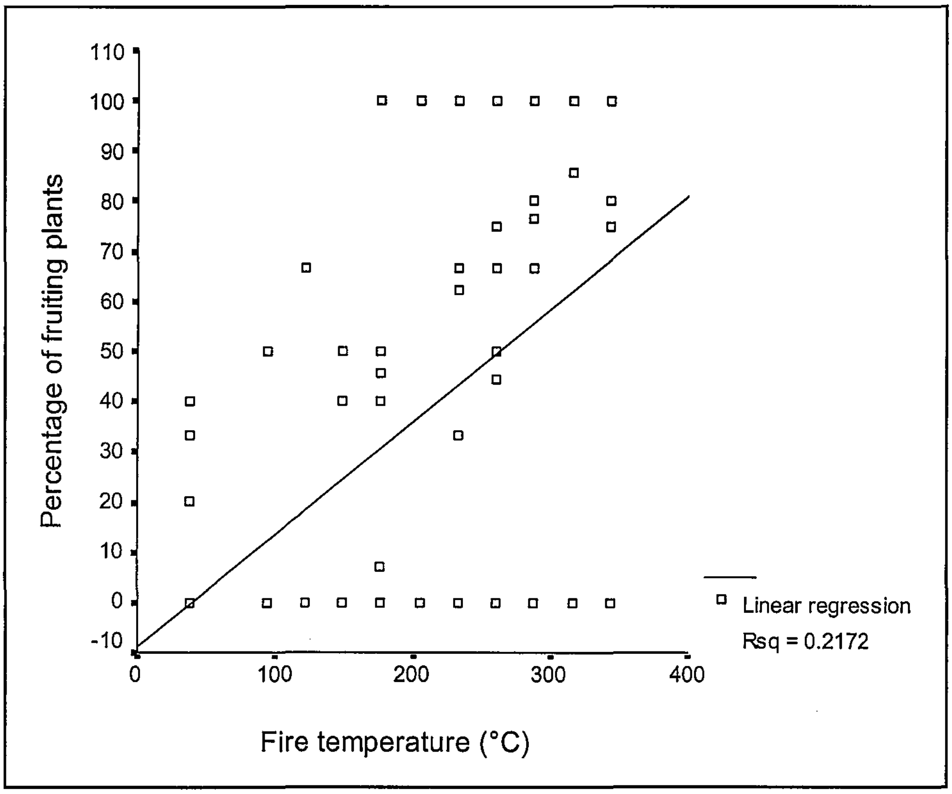

Figure 3. Scatterplot of mean number of fruits per reproductive plant of *Chamaecrista keyensis* the first year post-fire vs. maximum fire intensity.

Several studies have shown decreased seedling density with increased fire intensity due to higher seed mortality (Moreno and Oechel 1991, Odion and Davis 2000, Brooks 2002). Others have found the opposite trend, i.e., increased seedling density with increased fire intensity (Moreno and Oechel 1991, Spier and Snyder 1998). For example, *Jacquemontia curtissii*, another endemic herb of pine rockland, had greater seedling recruitment with higher fire intensity due to heat-stimulated seed germination (Spier and Snyder 1998). High fire intensity may also create safe sites for seed germination (e.g., with less duff and litter and better soil contact). Neither of these patterns was observed in

Table 2. Continued.

Factor	Vital rate					
	Mean number of fruits			Number of seedlings		
	MS	$F_{df1,df2}$	P	MS	$F_{df1,df2}$	P
Fire temp	5.04	$6.20_{1,42}$	**0.017**	0.07	$0.33_{1,50}$	0.566
site	3.79	$4.66_{2,42}$	**0.015**	1.17	$5.37_{2,50}$	**0.008**
Pyf	▨	▨	▨	0.09	$0.43_{1,50}$	0.514
Site* Pyf	▨	▨	▨	0.26	$1.21_{2,50}$	0.307
Fire temp	2.28	$2.16_{1,39}$	0.15	0.08	$0.85_{1,27}$	0.364
site	6.12	$5.81_{1,39}$	**0.021**	0.1	$1.10_{1,27}$	0.303
Pyf	▨	▨	▨	0.15	$1.65_{1,27}$	0.21
Site* Pyf	▨	▨	▨	▨	▨	▨

C. keyensis.

Similarly, *C. keyensis* mortality was not significantly affected by fire intensity, but was simply related to the presence/absence of fire. Mortality of *C. keyensis* was much higher in the presence of fire (Liu 2003). Yet for other species (e.g. *Jacquemontia curtisii*, *Pinus elliottii* var. *elliottii*), mortality was positively correlated with fire intensity (Tyler 1995, Ansley et al. 1998, Spier and Snyder 1998, Menges and Deyrup 2001). Vegetative growth of *C. keyensis* was also not significantly affected by fire intensity. In contrast, leaf production in *Zamia pumila* in Everglades National Park was greater after intense fires than after less intense ones (Negrón-Ortiz and Gorchov 2000).

It is difficult to compare fire intensity recorded in this study to others in the same ecosystem (e.g., Spier and Snyder 1998, Negrón-Ortiz and Gorchov 2000) due to differences in temperature recording methodology. The temperatures recorded here were those reached by the steel plates with substantial mass (128 g). Temperature-sensitive pellets on the ground as used in Spier and Snyder (1998) or in aluminum envelopes as used by Negrón-Ortiz and Gorchov (2000) will not necessarily record the same fire temperature as measured by our methodology. Since the temperature plates have substantial mass, our measurements integrated the heat released over time, whereas thermocouples measure more or less instantaneous temperature. Temperature plates may provide a better indication of how surface soils or the bases of plants heat up than thermocouples.

Implications for Chamaecrista keyensis fire management

In this study we showed that fire intensity had positive effects on fruit production. While high fire intensity is usually associated with heavy vegetation (Snyder et al. unpubl. data) resulting from long-term fire exclusion, these data do not suggest that long fire return intervals would benefit the long-term health of *C. keyensis* population for two important reasons: (1) *C. keyensis* density declines in long unburned patches, and (2) the response of increased fruit production to fire intensity is short term (only one-year post-fire). Short-term effects on one or two components among *C. keyensis*'s vital rates are not enough to compensate for the density decline that results from long fire return intervals. In addition, fire intensity is difficult to control, as it varies not only with weather and ignition patterns, but also within the burn unit. Therefore, considerations of fire management for *C. keyensis* should not rely solely on its response to fire intensity. Nonetheless, results from this study suggest that extremely low fire intensity, which may result from low fuel loads caused by very short fire return intervals (such as < 3 years), may not provide sufficient stimulation to reproduction for the best post-fire recovery of *C. keyensis*.

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Table 3. Effects of maximum fire temperature on presence or absence of seedlings of *Chamaecrista keyensis*: logistic regression analyses summary. Census plots with no melted paint were included. Italic indicates P < 0.1 level.

Year post-fire	Factor or covariate	Statistics		
		χ^2	df	P
Year 1	Fire temperature	0.23	1	0.629
	Site	4.13	2	0.127
	Previous year fruit	1.42	1	0.234
	Site * previous year fruit	0.65	2	0.722
Year 2	Fire temperature	1.84	1	0.175
	Site	0.11	1	0.738
	Previous year fruit	3.05	1	*0.081*
	Site * previous year fruit	0.11	1	0.743

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