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Examining the influence of mid-tropospheric conditions and surface wind changes on extremely large fires and fire growth days

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ABSTRACT

Background. Previous work by the author and others has examined weather associated with growth of exceptionally large fires ('Fires of Unusual Size', or FOUS), looking at three of four factors associated with critical fire weather patterns: antecedent drying, high wind and low humidity. However, the authors did not examine atmospheric stability, the fourth factor. **Aims.** This study examined the relationships of mid-tropospheric stability and dryness used in the Haines Index, and changes in surface wind speed or direction, to growth of FOUS. **Methods.** Weather measures were paired with daily growth measures for FOUS, and for merely 'large' fires paired with each FOUS. Distributions of weather and growth were compared between the two fire sets graphically and statistically to determine which, if any, weather properties correspond to greater growth on FOUS than on large fires. **Key results.** None of the factors showed a robust difference in fire growth response between FOUS and large fires. **Conclusions.** The examined measures, chosen for their anecdotal or assumed association with increased fire growth, showed no indication of that association. **Implications.** Focus on wind changes and mid-tropospheric properties may be counter-productive or distracting when one is concerned about major growth events on very large fires.

Keywords: atmospheric stability, extreme fire behaviour, fire growth, fire weather, wind shift.

Introduction

It is a wildfire's sensitivity to the weather, not the weather *per se*, that results in some fires growing larger and faster than others. This was one of the key results of Potter and McEvoy (2021) – hereafter, PM – which sought to understand how weather contributes to the daily and overall growth of some of the largest and fastest growing fires. They named these Fires of Unusual Size, FOUS, defined by three specific measures:

1. Final size greater than 36 400 ha (90 000 acres);
2. At least one daily growth event where the scaled linear growth rate (described below) exceeded 2.5;
3. The fire grew at least 8900 ha (22 000 acres) after the growth event described in criterion 2, above.

PM found that FOUS tend to occur after periods of higher atmospheric evaporative demand than other large fires (LFs) between 10 100 and 30 300 ha (25 000 and 75 000 acres). Surprisingly, once the fires start, median daily weather during FOUS appears slightly less conducive to fire growth (e.g. cooler, less windy, or more humid) than it does during the LFs examined. Wind speed and measures combining wind speed with low moisture corresponded to the most disparate growth on FOUS compared with their paired LFs. It is primarily the greater growth at higher wind speeds that appears to make an FOUS. High wind speed outliers – more than 1.5 times the interquartile range above the median – produced especially high growth response.

PM focused on temperature, atmospheric moisture (relative humidity and vapour pressure deficit) and wind speed. They noted that while their work considered three of the key components of critical fire weather patterns (antecedent drought, low humidity and strong winds), they did not examine the fourth component, instability. Critical fire weather patterns have been used in operational fire weather forecasting and fire behaviour training for half a century. Potter (2012) and Werth *et al.* (2016) provide summaries of the research history behind them, and Werth *et al.* (2016) also describes critical fire weather patterns for various parts of the United States.

The potential role of instability in fire behaviour goes back to Hayes (1947) in the United States, and Foley (1947) in Australia. Both authors discussed surface-based instability in the atmosphere immediately above the ground and how it produces turbulence and gusty winds, which can in turn influence fire spread. Later researchers, starting with Crosby (1949), considered instability of the atmosphere in layers above, and separated from, the ground. Two of the most notable and influential studies that promoted above-surface stability as a factor in critical fire weather patterns are Brotak (1976) and Haines (1988). Both studies examined stability in layers spanning upwards from 950 to 500 hPa. Haines (1988) implemented this concept in what is now known as the Haines Index, used operationally around the United States and in other parts of the world.

Although stability's contribution to critical fire weather is taught and used operationally, it is not clear how the *theoretical* association between stability aloft and fire behaviour on the ground manifests in reality. What Brotak (1976) referred to as 'unstable' was not dry thermodynamic absolute instability ($>10\,\mathrm{K\,km^{-1}}$ lapse rate), it was merely less stable than the standard atmospheric lapse rate ($6.5\,\mathrm{K\,km^{-1}}$), a use of terminology that has contributed to a half century of misuse of the term 'unstable'. Potter (2018) examined performance of the Haines Index and its components and found that overall, the stability component of the Haines Index performs poorly as a discriminator between small- and big-growth days for any cutoff between those two categories from 500 to 3000 ha. Despite these issues, the fire management community continues to use the Haines Index and to view mid-tropospheric 'instability' as a signal of potential explosive ('blow-up') fire behaviour.

PM focused on surface wind speed at 00 UTC (16 or 17 Local Time in Pacific or Mountain Standard Time, respectively), which is broadly within the peak of daily fire activity, but it is certainly true that other wind characteristics may elicit different growth from FOUS and LFs. Changes in wind direction and speed, specifically, are concerns for firefighter safety and may also result in large area growth. An idealised wildfire consists of an actively burning head on the downwind side, and flanks approximately parallel to the wind (Fig. 1). The head is the most intense portion of

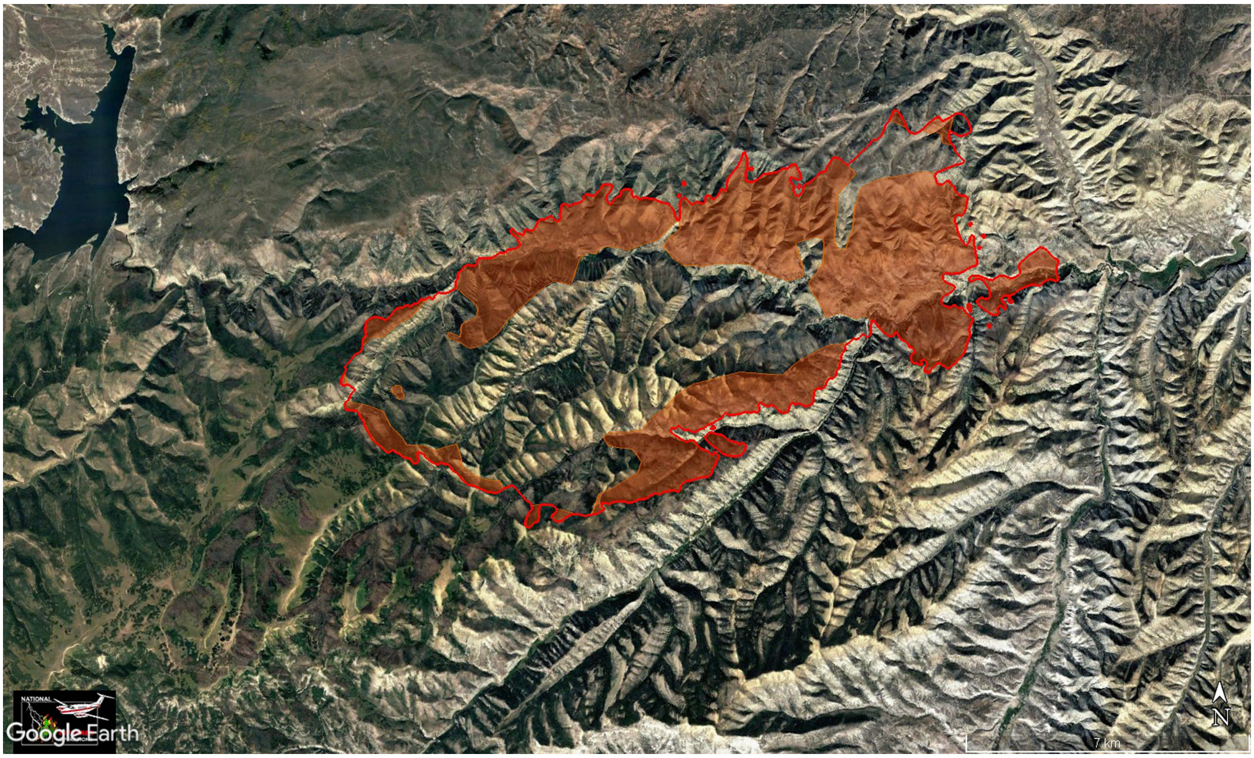

Fig. 1. Perimeter (solid red line) and active burning ('intense heat') area (red shading) illustrating the actively burning head of a wildland fire and the trailing flanks common on wildland fires. This image is from the Dollar Fire in Utah, captured on 3 July 2018 at 20:47 Local Daylight Time (LDT). Observed winds on the day of the image were from W to SW at 5–7 $\mathrm{m\,s^{-1}}$ measured at the nearby Horse Ridge Remote Automated Weather Station (14 km south of the fire, not shown in the figure).

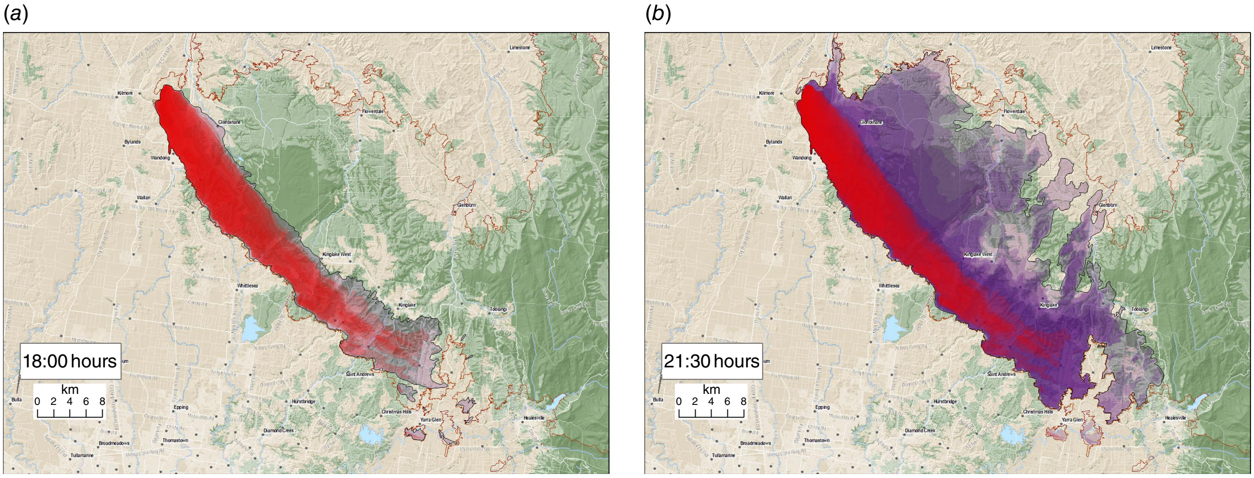

Fig. 2. Previously burned area (red) and actively burning area (purple) for the Kilmore East Fire in Victoria, Australia, 7 February 2009: (*a*) shows the fire's alignment with prevailing northwesterly winds at 18:00 LDT, prior to frontal passage and shift in wind direction; (*b*) shows how the northeast flank became a 50 km long head-fire by 21:30 LDT, a couple of hours after the winds shifted to southwesterly LDT. North is at the top of the figures.

the fire and management efforts focus on the less intense flanks. But if a fire has long flanks and there is a change in wind direction, the downwind flank becomes the new head and can lead to large areas burning as the new, wider head advances. Fig. 2 illustrates this happening on the Kilmore East Fire in Australia (Black Saturday, 7 February 2009). The fire was initially driven to the southeast by intense northwesterly prefrontal winds, which turned to southwesterly as a front arrived and changed the northeast flank of the fire to a head nearly 50 km long.

In the present study, I expand on PM's results by examining mid-tropospheric stability and measures of surface wind change, and how these properties relate to daily growth on FOUS versus LFs. For completeness, I also examine the mid-tropospheric moisture components of the Haines Index. While Potter (2018) examined the statistical skill of the Haines Index and its components on the same set of fires used here, the analysis and framing were directed at different questions than those considered presently.

Methods

Data

Fires

The fires and daily growth data used here are the same as those used in PM, and an abbreviated description is presented here. Twenty FOUS from the period 2004–2017 were considered, based on completeness of the daily data available for each and the period of overlap with the meteorological data. These FOUS are defined by the three criteria noted previously. For each FOUS, a counterpart LF was identified. Associated LFs are between 10 100 and 30 300 ha in final size, and were chosen for proximity to their respective FOUS. All the LFs used here were within 100 km of their corresponding FOUS, and usually within 60 km. Fig. 3 shows the locations of the FOUS and LFs used.

A best estimate of daily growth for each day, on each fire, was required. These were derived from multiple administrative and operational records, such as ICS-209 reports, airborne infrared measurements and progression maps. Notes from the reconciliation process and the final daily values used are available in Potter and McEvoy (2022).

Fire behaviour, including growth, depends on a wide range of weather factors, as well as fuel conditions (e.g. quantity, moisture content, spatial arrangement), terrain and management actions. Measurements of all of these potential influencing factors are rarely available, so other approaches must be used to identify the influence of the factors for which there are measurements. In this study, I focus only on the potential influences of weather factors on growth. The influences of fuels, terrain, management and any other factors must be considered as part of the residuals in the data. Indeed, as any one weather factor is examined, all other weather factors also contribute to the variance in the data. Geographic proximity of the FOUS and LFs is one constraint intended to reduce the magnitude of the differences in fire climate, vegetation and fuels between the paired fires.

I used three different measures of growth when evaluating the fires' response to a given weather measure. The first is area per day, A, commonly reported in acres but expressed as hectares here. The second is scaled area growth, A_s, where the growth on a given day is divided by the lifetime average daily growth for that fire.

$$A_{s\,i} = \frac{D}{A_f}(A_i - A_{i-1}) \tag{1}$$

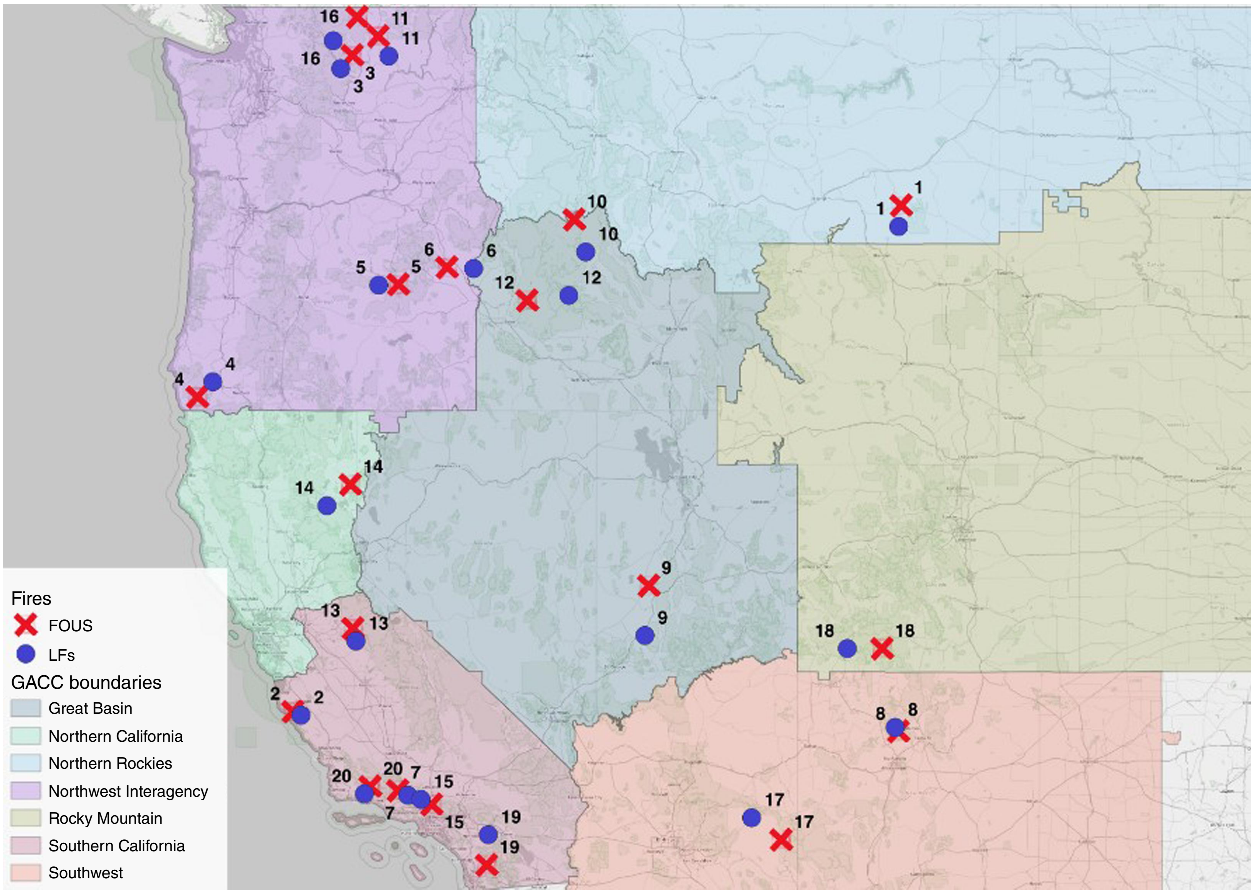

Fig. 3. Locations of FOUS and LFs used in this study. Shading indicates Geographic Area Coordination Center (GACC) boundaries.

$A_{s\,i}$ is the scaled area on day i; A_f is the final fire area; D is fire duration in days; A_i is fire area on day i. The difference in parentheses yields area per day, so that $A_{s\,i}$ is unitless.

The third is scaled linear growth, L_s, similar to A_s but using the square root of each day's area growth in order to produce a scaled linear spread rate.

$$L_{s\,i} = \frac{D}{\sqrt{A_f}}\left(\sqrt{A_i} - \sqrt{A_{i-1}}\right) \qquad (2)$$

PM found that A_s was the best growth measure for differentiating the growth response of FOUS and LFs, but for continuity and completeness, results for A and L_s are reported in Appendix 1.

Atmospheric data

Weather data were extracted from archived 00:00 UTC (Universal Time Coordinated) analyses of the North American Mesoscale Forecast System (NAM) grid 218 (12 km spacing). Analysis forecast hours 0, 12 and 18 (0, 12, 18 UTC) were used to represent western United States daytime conditions. For each day of each fire, weather measures were extracted from the NAM analyses for the grid cell closest to the location of the fire's point of origin.

Table 1. Weather measure symbols and descriptions.

Weather measure	Description
$\Delta T_{850-700}$	Temperature difference between 850 and 700 hPa
$\Delta T_{700-500}$	Temperature difference between 700 and 500 hPa
DPD_{850}	Dewpoint depression at 850 hPa
DPD_{700}	Dewpoint depression at 700 hPa
ΔV	Change in wind speed from previous day
$\Delta\theta$	Change in wind direction from previous day
$\lvert\Delta\theta\rvert$	Absolute value of $\Delta\theta$

Full descriptions are provided in the text.

Atmospheric properties

The weather properties examined here include two groups, summarised in Table 1. One is the basic quantities used in computing the Haines Index, which I refer to generally as the mid-tropospheric measures. The Haines Index consists of a stability component, expressed as the temperature difference between two prescribed pressure levels; and a moisture component, in the form of a dewpoint depression (DPD) at a prescribed pressure level. These components are converted to integer values of 1, 2, or 3 and added together to yield an index value from 2 to 6. There are three elevation variants of the Haines Index, using lower pressure levels for higher elevation locations. The low-elevation variant is not applicable for most locations in the western United States. I computed the components for the mid-level variant (850 hPa dewpoint depression and 850–700 hPa temperature difference) at 00 UTC for any day and location when model surface pressure was greater than 850 hPa. I computed the high-level variant components (700 hPa dewpoint depression and 700–500 hPa temperature difference) at all locations and days, again at 00 UTC.

Three wind measures are examined here, expanding on the basic 00 UTC wind speeds considered in PM. All three of these measures use the sum of the NAM 10 m wind vectors from 12, 18, and 00 UTC for a given local day. These are more representative of the winds over a full day than are the 00 UTC winds, and can potentially capture high wind speeds that occurred earlier in the day than 00 UTC.

Change in wind speed, ΔV, is the first of the wind measures. PM found 80th to 100th percentile 00 UTC wind speed appeared to elicit different growth responses for FOUS and LFs, especially on outlier high-wind speed days. Looking at the change in summed winds between days will show whether an *increase* in wind speed is as influential as the high wind speeds alone considered in PM. In other words, does a high wind have a different impact when it follows weaker winds than it does if it occurs on the second or later day in a series of high-wind days? The other two wind measures I examine are the change in wind direction, $\Delta\theta$ (positive in a right-handed, Cartesian sense) and the absolute value of that change.

In the remainder of this paper, greater mid-tropospheric temperature differences and dewpoint depressions, increases in wind speed and greater changes in wind direction (positive or negative) will be considered more conducive to fire spread. For all of the mid-tropospheric components, this is a fundamental part of their role in the Haines Index and the common understanding of the roles stability and dry air play in fire growth. Wind changes are not part of any index or specific metric for fire behaviour, but increasing wind speed and changing wind directions are frequently cited in operational discussions of fire behaviour and spread.

Analysis

The analysis here parallels that in PM so that the results can be more directly compared. It emphasises graphical summaries of the data, with inferential statistics in a secondary role (Wasserstein and Lazar 2016). Weather and growth results for the mid-tropospheric weather components are presented first, followed by results for the wind measures. The intent is to provide greater continuity for the reader on these two distinct, general areas of the meteorology. All graphs and statistical tests used R software (R Core Team 2018), including the *quantreg* library (Koenker 2020) for quantile regression.

Daily weather

Median daily weather measures (Table 1) are compared for each (LF, FOUS) fire pair by plotting them and comparing with the 1:1 line. Crosshairs on points indicate the spread from first to third quartile values for each weather property and pair. A point above (below) the 1:1 line indicates median weather values for a FOUS greater (less) than those for its corresponding LF. In addition to this comparison by pairs, weather measures are compared for all FOUS days and all LF days across all member fires in each group using standard box-and-whisker plots. Accompanying these visual comparisons, I subjected the aggregated distributions to two-sided Kolmogorov–Smirnov tests.

Growth response

'Growth' for the purposes of this paper is the change in fire size from one day to the next. 'Growth response' or 'response' is growth when compared with a specific weather measure or change in that measure. Response of the fires to the weather they experienced is examined using three comparisons: pairwise growth response for middle and top quintile weather; 80th quantile regression (Cade *et al.* 1999; Cade and Noon 2003) for all aggregated days in each fire group; and quantitative comparison of growth response on pair-based outlier weather days to average growth response for each fire.

For these tests, quintile breakpoints were determined using all of the daily values of a given weather measure for a given fire pair. The middle quintile represents 'average' conditions; the top quintile for all of the measures considered represents 'extreme' conditions. Similarly, outliers are based on the distribution of daily values of the given measure and fire pair and using the conventional definition of points more than 1.5 times the interquartile spread for that measure and pair.

Results

Mid-tropospheric measures

Daily weather

Pairwise comparison. Fig. 4 shows the results of the pairwise comparison for the mid-tropospheric measures. (Some fires were at elevations where surface pressure is below 850 hPa, resulting in fewer points in Fig. 4*a*, *b* than in Fig. 4*c*, *d*.) The temperature differences (Fig. 4*a*, *c*) cluster close to the 1:1 line and the group centroids lie very close to this line as well. The clustering indicates very similar ΔTs for the members of each (LF, FOUS) pair. As many or more points lie below the diagonals in the figures than above, suggesting equal or larger ΔTs for more of the LFs than for their FOUS counterparts.

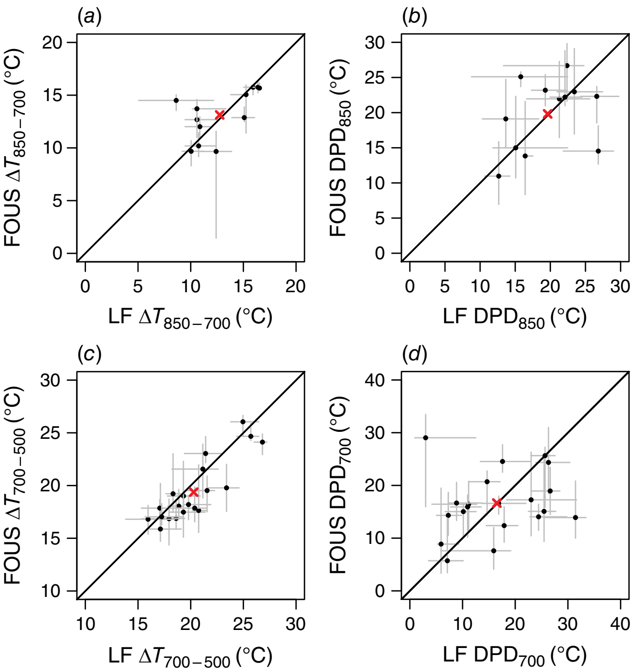

Fig. 4. Paired median values of (*a*) $\Delta T_{850-700}$; (*b*) DPD_{850}; (*c*) $\Delta T_{700-500}$, and (*d*) DPD_{700}. Solid black points indicate the median (LF, FOUS) values. Crosshairs indicate the 25th to 75th percentile values for each fire. In each panel the (red) X indicates the centroids of the median values over all fires.

Dewpoint depressions (Fig. 4*b*, *d*) are comparatively more scattered, indicating that within fire pairs, there are differences in fire-median DPDs. There are almost equal numbers of points above and below the diagonals for both mid- and high-level variants, indicating that LF DPD is greater than FOUS DPD approximately as often as the reverse is true. Group centroids are very close to the diagonals. In summary, there is more variability in DPD than ΔT among the fires, but across all fire pairs, DPD values appear comparable for paired LFs and FOUS.

Aggregate comparison. Box-and-whisker plots for aggregated mid-tropospheric properties (Fig. 5) reinforce the pairwise examination. The distributions for LFs and FOUS are very similar for each component. Median values for all properties are slightly lower for FOUS than for LFs, but almost imperceptibly so. The most striking feature is the number of high outliers of DPD_{700} for FOUS (Fig. 5*d*), associated with a smaller interquartile distance for this group.

To complement the box-and-whisker comparisons, Fig. 6 shows the empirical cumulative distribution functions (ecdfs) of the mid-tropospheric measures for the LF and FOUS sets. The *P*-values resulting from two-sided Kolmogorov–Smirnov tests for the measures are shown in the upper left corner of each panel. Visually, the ecdfs separate clearly for all four measures. The least separated pair is DPD_{850}, which is also the measure with the highest *P*-value, suggesting the LF and FOUS values of this measure are likely to share a common parent distribution function. For all four mid-tropospheric measures, the LF distribution shows higher values than the FOUS distributions, consistent with Fig. 5.

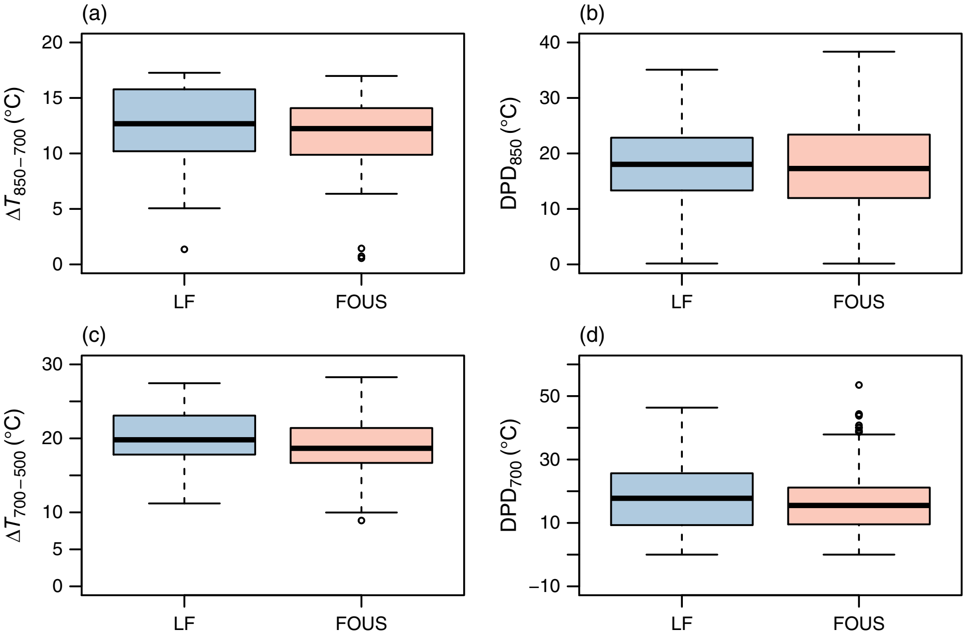

Fig. 5. Box-and-whisker plots for LF (blue) and FOUS (red): (*a*) $\Delta T_{850-700}$; (*b*) DPD_{850}; (*c*) $\Delta T_{700-500}$; and (*d*) DPD_{700}.

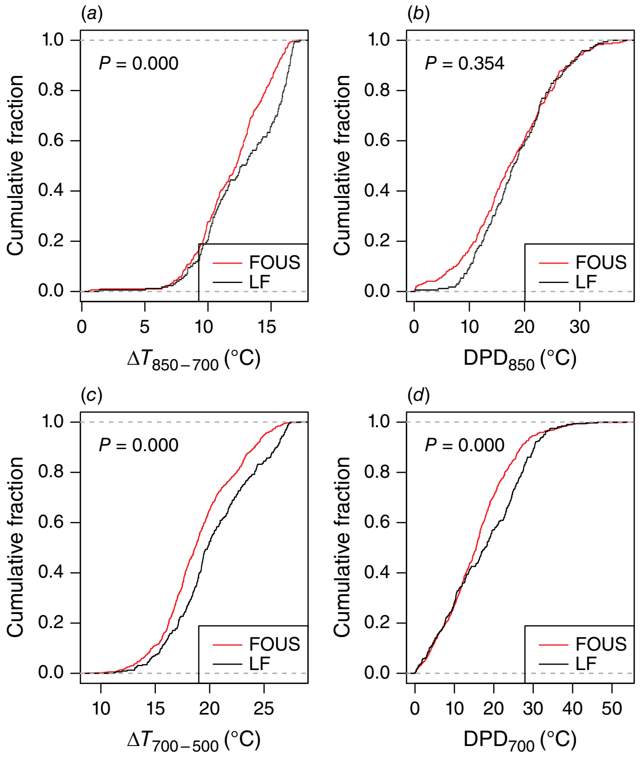

Fig. 6. Empirical cumulative distribution functions for (*a*) $\Delta T_{850\text{–}700}$; (*b*) DPD_{850}; (*c*) $\Delta T_{700\text{–}500}$; and (*d*) DPD_{700}. The *P*-values obtained by applying a two-sided Kolmogorov–Smirnov test to each weather measure are in the upper left corners of the panels.

Growth response to weather measures

Pairwise comparison. Figs 7, 8 show the growth response to mid-tropospheric measures when those measures are in their pair-based middle quintiles (Fig. 7) and upper quintiles (Fig. 8). For mid-quintile weather, FOUS growth response is greater than LF for all measures except $\Delta T_{850-700}$. For DPD_{850} and $\Delta T_{700-500}$, the FOUS response is greater for a majority of the fire pairs, while for DPD_{700}, the proportion of pairs where FOUS growth exceeds LF growth is close to half. Fig. 7*c* indicates FOUS growth response for middle quintile $\Delta T_{700-500}$ is almost twice that for LF, as well as approximately twice lifetime-average growth. The magnitude of mean growth (centroid values for LFs and FOUS) shows the LFs growing at or well below average for the midrange values of all four mid-tropospheric measures. The same is true for FOUS growth for midrange $\Delta T_{850-700}$ and DPD_{850}.

These relationships almost all reverse for growth response to upper-quintile, more fire-conducive weather conditions. For all measures except $\Delta T_{850-700}$, LF growth response exceeds FOUS growth response under these extreme conditions. FOUS growth response under top quintile conditions is above lifetime average for $\Delta T_{850-700}$ and DPD_{700}, but below for DPD_{850}. LF growth response was comparably above average for DPD_{700}.

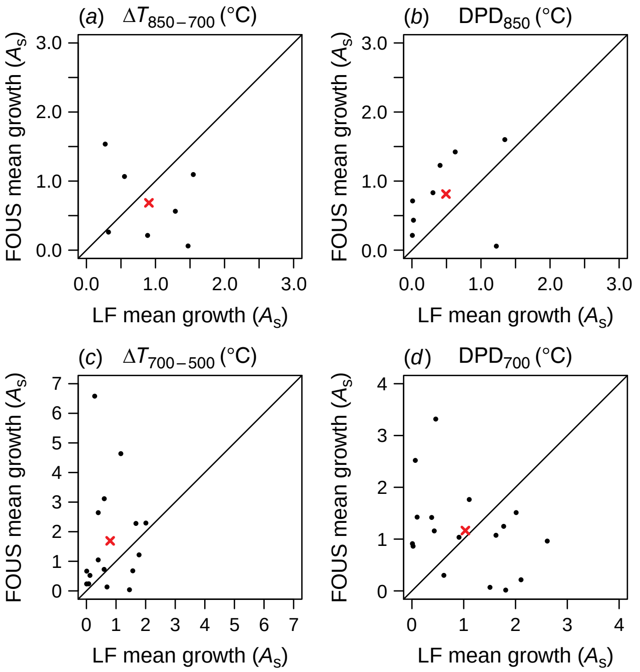

Fig. 7. Comparison of mean growth response to pair-based middle quintile (40th to 60th percentile) weather conditions for (LF, FOUS) pairs: (*a*) $\Delta T_{850\text{–}700}$; (*b*) DPD_{850}; (*c*) $\Delta T_{700\text{–}500}$; and (*d*) DPD_{700}. In each panel the (red) X indicates the mean growth response across all (LF, FOUS).

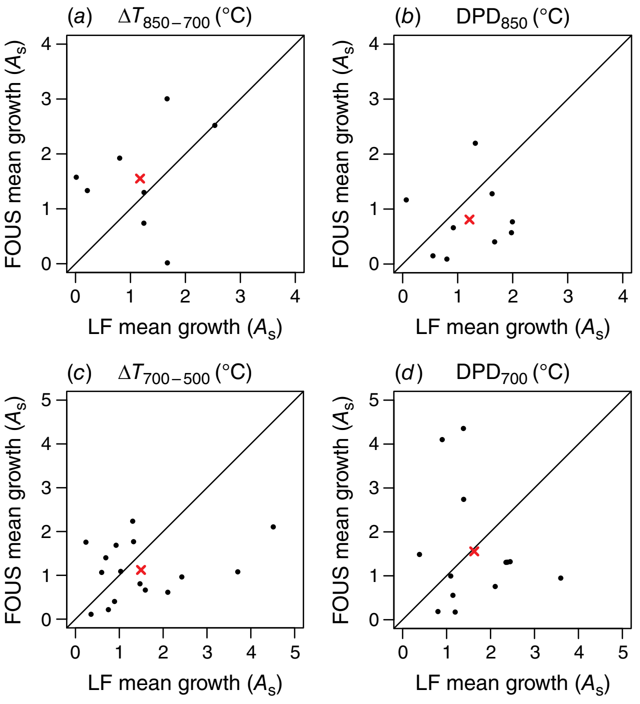

Fig. 8. As Fig. 7 but for pair-based top quintile (80th to 100th percentile) weather conditions.

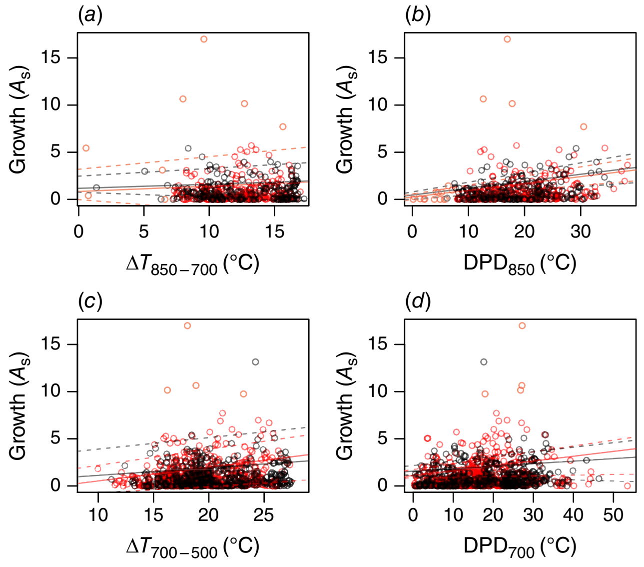

Fig. 9. Growth response to mid-tropospheric weather measures aggregated for FOUS (red) and LF (black): (*a*) $\Delta T_{850-700}$; (*b*) DPD$_{850}$; (*c*) $\Delta T_{700-500}$; and (*d*) DPD$_{700}$. Open circles indicate individual daily values for fire in each set. Solid lines are the best-estimate linear 80th quantile regression, dashed lines show the bounding envelopes of slope and intercept estimates provided by R software.

Aggregate comparison. When all LF fire days are compared with all FOUS days using 80th quantile regression (Fig. 9), there is very little difference in growth response between the two groups of fires. For $\Delta T_{850-700}$ and DPD$_{850}$, the regression lines have very similar slopes and intercepts, and fall within each other's best estimate envelopes. The slopes for $\Delta T_{850-700}$ are close to zero, but growth response to DPD$_{850}$ does appear to have a positive slope.

Regressions for $\Delta T_{700-500}$, and DPD$_{700}$ each have less similar slopes for the two sets of fires. For each measure, slopes are positive, but the best estimates for the LF data cross those for the FOUS. This is consistent with the pairwise comparison results for mid- and top-quintile growth response. It also indicates FOUS may respond to lower values of these weather measures less strongly than LFs do, but they respond more strongly than LFs to higher values of these two measures.

Growth response to outlier weather days. Growth on days with high outlier values (Table 2) of the mid-tropospheric measures was greater than lifetime average growth on FOUS for all four measures. It was also twice the average for DPD$_{700}$ for LF, but only marginally different from average LF growth on the other measures. There is therefore some indication that FOUS growth response is greater than LF response on days with high outlier values of $\Delta T_{850-700}$, DPD$_{850}$, and $\Delta T_{700-500}$, but outlier DPD$_{700}$ affects both types of fires comparably, and strongly.

Table 2. Ratio of growth on high outlier days to lifetime-average growth across all fires in each set.

Variable	No. FOUS	No. LFs	FOUS ratio	LF ratio
DPD$_{850}$	2	2	1.46	1.06
$\Delta T_{850-700}$	3	2	1.68	0.75
DPD$_{700}$	6	4	2.43	2.10
$\Delta T_{700-500}$	5	2	1.95	0.900
$\Delta\theta$	3	6	0.758	0.702
$\lvert\Delta\theta\rvert$	8	4	0.684	0.481
ΔV	7	7	2.29	1.07

The number of fires with outliers for a given weather property is provided, since not every fire had outlier days for any given weather property.

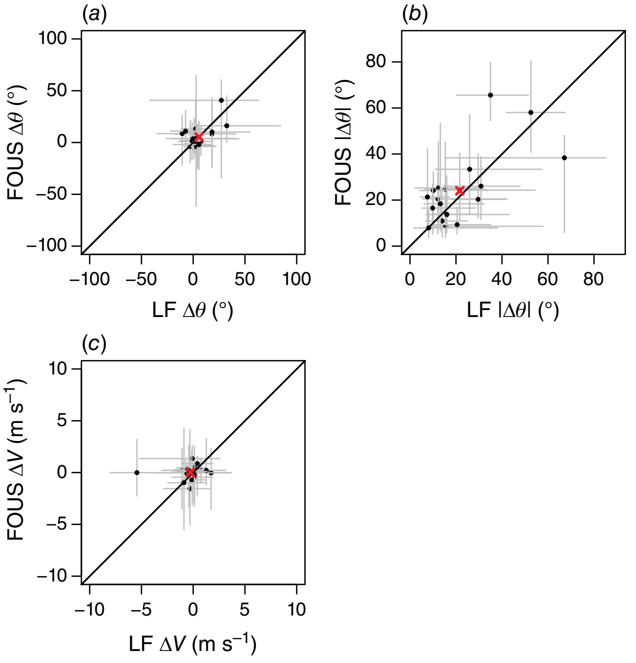

Fig. 10. As Fig. 4 but for (*a*) $\Delta\theta$; (*b*) $\lvert\Delta\theta\rvert$; (*c*) ΔV.

Wind change measures

Daily weather

Pairwise comparison. Looking at the daily values of the wind change measures in terms of fire pairs (Fig. 10), there is some scatter across the diagonals but the all-pair centroids of these properties lie close to those diagonals. For $\lvert\Delta\theta\rvert$, there are a few more pairs where the FOUS median is greater than the paired LF median, and the centroid is slightly on the FOUS side of the diagonal.

Aggregate comparison. Aggregate wind characteristics (Fig. 11) similarly show little difference in the distributions between LFs and FOUS. The number of ΔV outliers is notable. When the daily values of all FOUS and LFs are thus examined in aggregate, there are more FOUS outliers than LF outliers

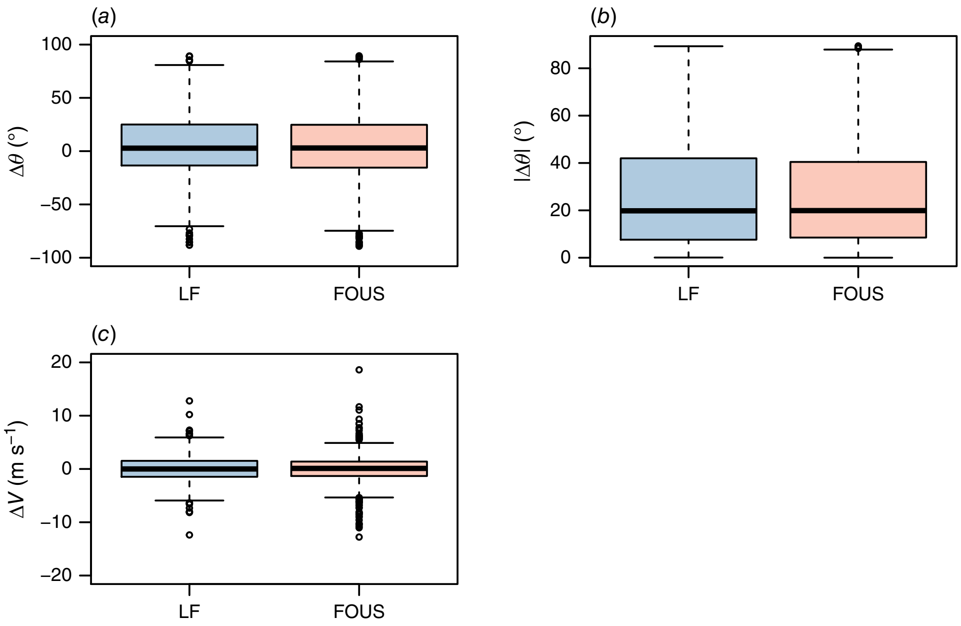

Fig. 11. As Fig. 5 but for (*a*) $\Delta\theta$; (b) $|\Delta\theta|$; (*c*) ΔV.

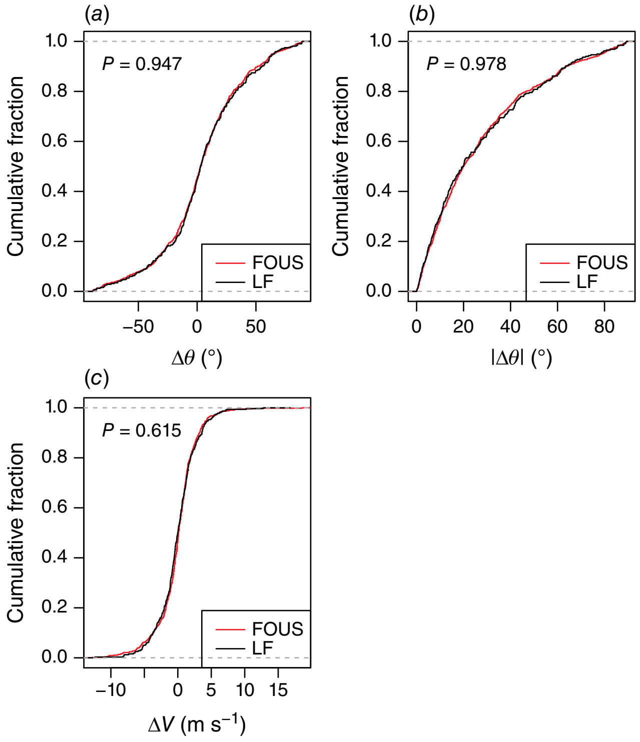

Fig. 12. As Fig. 6, but for (a) $\Delta\theta$; (b) $|\Delta\theta|$; (c) ΔV.

even though the medians and interquartile distances appear similar for the two groups.

The ecdfs and *P*-values for wind speed and direction changes (Fig. 12) show very little difference between the LF and FOUS distributions. There is no consistent displacement of one ecdf relative to the other, and the *P*-values indicate high probabilities that the LF and FOUS data for any given measure come from the same parent distribution.

Growth response to weather measures

Pairwise comparison. Growth response to pairwise middle quintile values of $\Delta\theta$ (Fig. 13) is greater for FOUS than for LF, but for $|\Delta\theta|$ and ΔV, the two sets of fires respond comparably to middle-quintile weather conditions. The number of fires above the diagonal (i.e. growth response greater for the FOUS pair member) and below the diagonal is comparable for all of the measures. Because $\Delta\theta$ and ΔV can be positive or negative, the middle quintile ranges of these properties bracket the zero point for most of the fire pairs. The middle quintiles for $|\Delta\theta|$ range from approximately 30° to 45° and cannot be directly compared with the $\Delta\theta$ results.

High quintile growth response to $\Delta\theta$ and ΔV, shown in Fig. 14*a*, *c*, is slightly greater for FOUS than for LF. For both measures, median growth response of most pairs, and overall group mean growth response, falls on the FOUS side of the diagonal. Furthermore, LF growth response for these upper quintile conditions averaged approximately one, the lifetime average. Slightly more points lie above the diagonal than below for $|\Delta\theta|$ (Fig. 14*b*) and the mean centroid is very close to the diagonal and a scaled growth of one. Growth on days with greater changes in wind direction or speed is only slightly greater than overall average growth on the individual fires.

Because ΔV and $\Delta\theta$ can be positive or negative, thoroughness requires considering the possibility that fire growth responds differently to extreme negative (first quintile) and extreme positive (fifth quintile) values. Comparing these responses (first quintile not shown) indicated very little

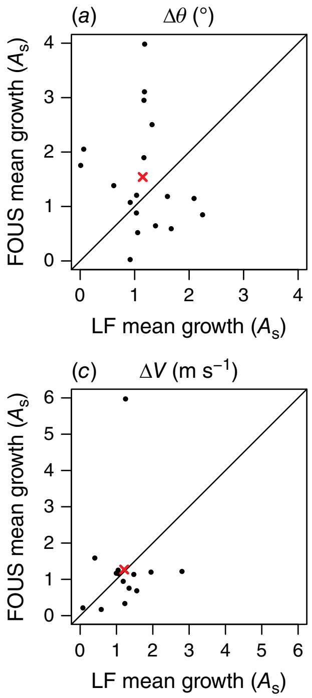

Fig. 13. Comparison of mean growth response with pair-based middle quintile (40th to 60th percentile) weather conditions for (LF, FOUS) pairs: (*a*) $\Delta\theta$; (*b*) $|\Delta\theta|$; and (*c*) ΔV. In each panel the (red) X indicates the mean growth response across all (LF, FOUS).

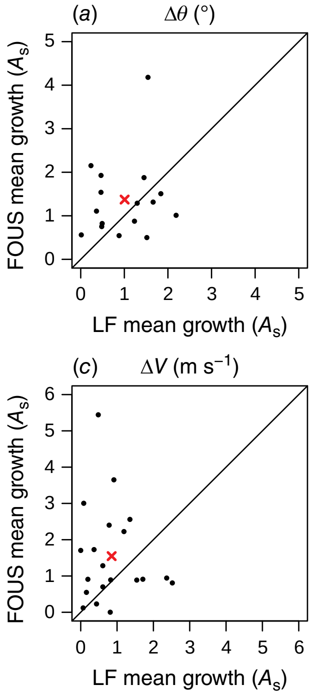

Fig. 14. As Fig. 13 but for pair-based upper quintile (80th to 100th percentile) weather conditions for (LF, FOUS).

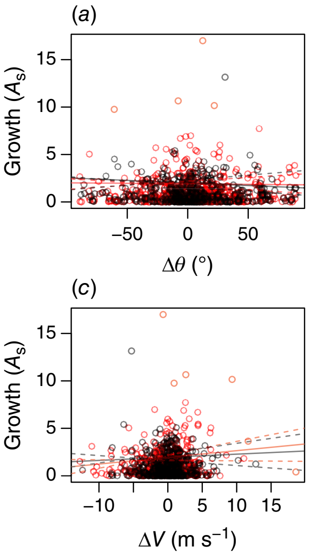

Fig. 15. Growth response to wind change measures aggregated for FOUS (red) and LF (black): (*a*) $\Delta\theta$; (*b*) $|\Delta\theta|$; and (*c*) ΔV. Open circles indicate individual daily values for fire in each set. Solid lines are the best-estimate linear 80th quantile regression, dashed lines show the bounding envelopes of slope and intercept estimates provided by R software.

difference between FOUS and LF growth response for either first or fifth quintile values of ΔV or $\Delta\theta$.

Aggregate comparison. When growth response on all FOUS days is compared with all LF days (Fig. 15), there is little response difference reflected in the 80th quantile regressions for the two sets for any of the wind change measures. In each case, the best fit regression for each of the fire sets lies fully within the estimate bounds for the other set. The slopes are also very shallow, meaning little growth response to the weather measures. The greatest slope is for ΔV, but again the slopes are similar for LF and FOUS days. Furthermore, the estimate bounds for both sets include both positive and negative slopes.

Growth response to outlier weather days. Growth response on days when the weather measures were outliers within their pairs (Table 2) was greater than average for ΔV, but less than average for both $\Delta\theta$ and $|\Delta\theta|$. For FOUS, ΔV outliers produced 2.3× lifetime average growth, whereas for LF, these days produced 1.1× that average. These responses are comparable with, but smaller than, those found by PM for surface wind speed.

Discussion

The mid-tropospheric and wind change measures considered here each spanned similar ranges for both FOUS and LF, with similar distributions. The slight differences showed LF occurred during weather that was more conducive to fire growth. Distributions of $\Delta T_{850-700}$, DPD_{700} and ΔV were narrower for FOUS but with more outlier values. This general pattern matches PM's results for the weather measures they examined. As they noted, the pattern is consistent with more persistent, moderate weather punctuated by stronger outlier events during FOUS than LFs. The narrower distribution of ΔV for FOUS in Fig. 11 further supports this hypothesis. The magnitudes of means appear less important than the magnitude of outlier events. Duration of weather patterns (i.e. ridges and troughs) may also differ for LFs versus FOUS but was not part of this study.

With respect to growth response, none of the weather measures considered here had an impact comparable with what PM found for top-quintile wind speed, or wind speed combined with aridity measures. Current results were more comparable with those PM obtained for surface temperature and relative humidity – weak response overall, and little difference in response between FOUS and LFs. None of the weather properties examined here appears to be associated with different growth on FOUS versus LFs.

For each of the measures considered here, results of the various comparisons were inconsistent regarding their association with greater growth response on FOUS or LF. The most consistent results were those for $\Delta T_{850-700}$ and ΔV. Even for $\Delta T_{850-700}$, top quintile response was greater for LF than for FOUS, but the middle quintile, 80th quantile regression and outlier growth were all greater for FOUS. For ΔV, LF response was greater than FOUS for middle quintile conditions, but FOUS response was greater for the other tests. The results for ΔV are the closest to the stronger results from PM. In the *Methods* section, I asked whether an *increase* in wind speed is as influential as high wind speeds alone. The answer from this analysis appears to be 'No'. It is possible that the impact of an increase depends on the initial wind speed, or on other factors such as alignment with terrain. This was beyond the scope of the present study, but is a potential area for further work.

The properties used for the midlevel Haines Index, $\Delta T_{850-700}$ and DPD_{850}, had the most variable results. For fires in the mountainous western United States, 850 hPa can be close to the ground, and surface pressure can be lower than 850 hPa. This means surface solar heating and air temperatures can influence these measures, and the measures can be more indicative of conditions in the surface layer than the free atmosphere. A more detailed examination of growth response and the distance between the surface and 850 hPa might clarify the influence of surface-layer versus free-atmosphere conditions on LFs versus FOUS, or growth in general.

The results for $\Delta\theta$ and $|\Delta\theta|$ may be too simplistic. Of all the weather properties considered here and in PM, these are the most likely to have a non-monotonic growth response, specifically a response with a maximum value in the midrange of the weather property. In the extreme case of a 180° shift – a full reversal – winds would push a fire into previously burned area, unlikely to spread or grow substantially. Depending on the mix of fine fuels (to carry the head forward) and coarse fuels (to sustain combustion and increase flaming depth), the optimum $\Delta\theta$ for greatest growth response could be more in the 30–90° range (arbitrary values chosen solely to illustrate the point). Alignment of the wind direction with terrain features before or after the wind shifts is known to be a strong influence on fire growth, but is beyond the capabilities of the present data to address. Figs 13*b*, 15*a, b* suggest high growth response for $|\Delta\theta| < 50^\circ$ and further exploration of non-linear response could be fruitful. Alternatively, perhaps consistent wind direction ($\Delta\theta = 0$) elicits the greatest growth response.

One key motivation for this study was to examine the fourth component of critical fire weather patterns, stability. Results for both stability measures examined here are ambiguous and the growth response to them is weak for both FOUS and LFs, relative to the results for the other components, in PM. Given these results, the history of misuse of the term 'stability' discussed in the introduction and the results of Potter (2018) that the Haines Index stability components demonstrated little skill in predicting fire growth, the relevance of mid-tropospheric stability as a meaningful part of critical fire weather patterns is doubtful.

In their *Conclusions*, PM raised the question of how the durations and frequencies of ridges and troughs contribute to FOUS. They speculated that FOUS develop under more persistent but weaker ridges, punctuated by fewer, stronger troughs that produced strong winds. The present results lend little further insight to this question. They do not include any temporal characteristics of the weather measures, the most direct way to answer the question. The narrower distributions of ΔV and $\Delta\theta$ for FOUS than for LF, with more outliers, are consistent with their speculation – many days with small changes, but some notably large changes, as well.

Conclusions

Science has an equal obligation to report both positive and negative results of research, though historically publication of negative results has been difficult. The negative results presented here – specifically, the finding that the mid-tropospheric and wind change measures do not appear to result in any greater growth on FOUS than on LFs – advance understanding of weather and FOUS by largely dismissing these measures from the list of likely differentiating factors. Elimination of potential factors currently codified in operation is a valuable contribution to the state of understanding large daily growth events. It allows the research community to focus on exploring other controls on growth, and the operational community to concentrate on the conditions that actually influence the fires they are dealing with.

This analysis is intentionally simple, and the straightforward approach leaves many questions open for further study. Fuel characteristics and terrain undoubtedly contribute to fire growth. Whether they contribute differently to FOUS than to other fires is unknown. Interactions between or among various growth drivers also merit examination. Specific examples include wind direction relative to terrain features, and the combination of wind speed and change in wind speed. It is also possible that one driver generates a different response on FOUS versus LFs, but only within a certain range of a second driver. Purely as an illustrative example, $\Delta T_{850-700}$ may differentiate growth only for low surface wind speeds.

Any questions involving subranges or interactions of growth drivers will require a larger data set. Fortunately, the number of identified FOUS has grown significantly. The original list of FOUS from 2004 to 2017 included 20 fires, 4 of which were complexes, and that list did not include all of the potential FOUS from that period. There were 11 candidate FOUS in 2021, 1 of these a complex. At present I have confirmed 17 FOUS for 2020, with 12 others unconfirmed. Seven of the unconfirmed cases are complexes, yielding a possible 29 FOUS for 2020, or 22 if complexes are not used. For the period 2004–2021, there are thus at least 48 confirmed FOUS, 12 more potential FOUS, and up to 12 FOUS complexes. These numbers are sufficient to do more detailed and complicated analyses including interactions between multiple weather factors; importance of fuels or fuel conditions; terrain alignment of winds; differences between complexes and non-complexes; and spatial or temporal compositing of multiple fires in smaller geographic areas.

As Potter and McEvoy (2021) noted, the results here are highly relevant to assessment of future fire conditions. Any effort to predict changes in the future frequency of extreme fire growth events must rely on the factors – weather or otherwise – that are actually known to drive such events, and not on factors that have shown no relationship to these events. Otherwise, projections of future climate impacts will rest on incomplete or flawed understanding of what truly leads to the biggest fire runs, and to fires of unusual size.

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Data availability. Fire growth and post-processed weather data used for this study are available at https://doi.org/10.2737/RDS-2022-0040.

Conflicts of interest. Brian Potter is an Associate Editor of International Journal of Wildland Fire. To mitigate any potential conflict of interest he was blinded from the review process and was not involved at any stage in the editorial process for this manuscript.

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Appendix 1. Growth response for unscaled area and scaled linear growth

To complete the parallel with results in Potter and McEvoy (2021), this appendix contains results for the growth response analysis using unscaled area (A) and scaled linear growth (L_s). For L_s, as for A_s, lifetime average growth for every fire is one, by definition. This is an important reference value when examining whether growth is low, average, or high for some specific set of weather conditions. Average area growth for all FOUS days in this study was 5600 ha, while for LF days it was 1600 ha. These values show that FOUS grow more on average than LF, and again serve as reference points for what constitutes low, average, or high growth.

Mid-tropospheric measures

Figs A1, A2 show pair-wise growth response using area, A, as the measure of growth. For middle quintile weather conditions (Fig. A1), FOUS growth was greater than LF for all of the mid-tropospheric measures, and for more pairs. This is also true for all measures except DPD_{850} under top-quintile weather conditions (Fig. A2). The latter shows very similar growth response for FOUS and LF. Area growth response of FOUS is below lifetime average for both middle- and top-quintile DPD_{850}. When all fires in each set are aggregated, 80th quantile regressions (Fig. A3) show almost no difference between the regressions for $\Delta T_{850-700}$ and DPD_{850}. The regressions for the higher-altitude measures, $\Delta T_{700-500}$ and DPD_{700}, are distinct for the FOUS and LF data and outside each other's estimate likelihood bounds.

Collectively these results suggest that area growth response for FOUS is greater than that for LFs for $\Delta T_{700-500}$ and DPD_{700}. The lower-level mid-tropospheric measures show some response difference on a pairwise basis, but not in aggregate. This is similar to what PM found for surface temperature and relative humidity – comparative growth in acres is inconsistent across the applied tests.

When growth is measured as L_s (Figs A4, A5), there is little difference in response for either middle or high quintile mid-tropospheric weather measures. Response to middle-quintile $\Delta T_{700-500}$ is slightly greater for FOUS, and above life-time average. For top-quintile DPD_{850}, response is greater for LF than for FOUS. This is true of the paired fire centroid, as well as most of the individual fires.

When evaluated using quantile regression (Fig. A6), L_s response is both very flat and very similar between the two fire sets for $\Delta T_{850-700}$. Response to DPD_{850} is greater for LFs than FOUS, though the regression estimates for the two sets are within each other's estimate envelopes. With respect to $\Delta T_{700-500}$, LF response is almost flat – no visible change in growth as $\Delta T_{700-500}$ increases. FOUS response is not as flat, and is less than LF at lower values of $\Delta T_{700-500}$ but greater for $\Delta T_{700-500}$ above ~21°C. The two sets' regressions do fall within one another's estimate envelopes, however. The DPD_{700} growth response for FOUS and LFs is very similar, and has a positive slope.

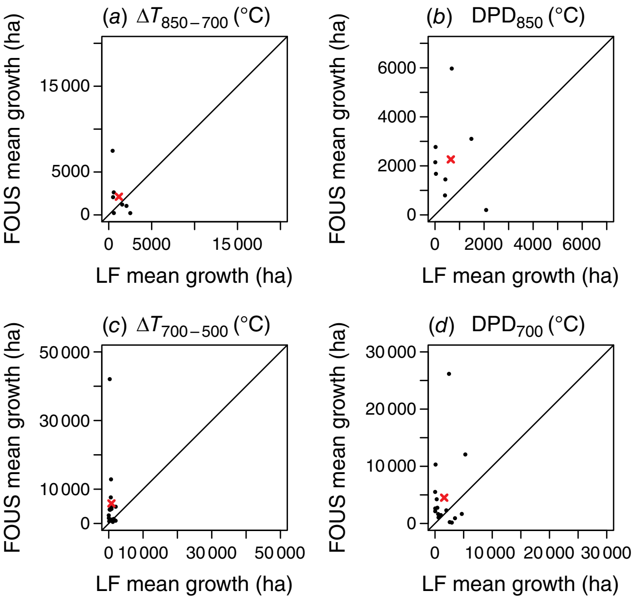

Fig. A1. Paired mean unscaled area growth (A, ha) response for pairwise third quintile (40th to 60th percentile) weather: (*a*) $\Delta T_{850-700}$; (*b*) DPD_{850}; (*c*) $\Delta T_{700-500}$; and (*d*) DPD_{700}. In each panel the (red) X indicates the mean growth response across all (LF, FOUS).

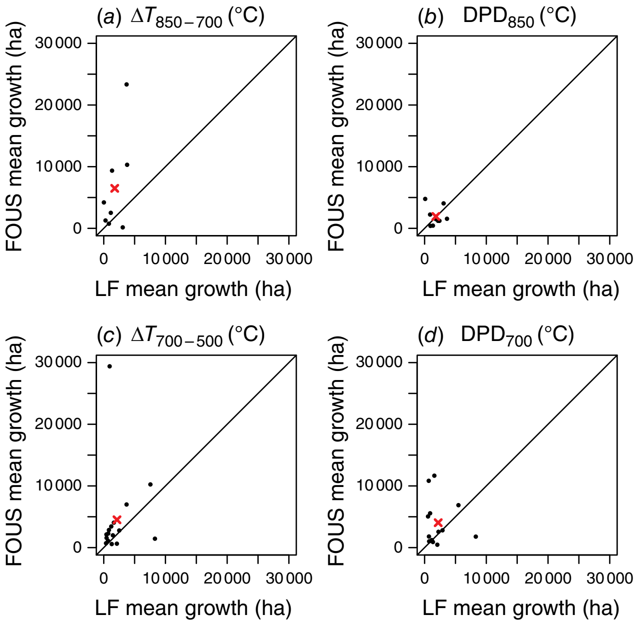

Fig. A2. As Fig. A1 but for pairwise fifth quintile (80th to 100th percentile) weather.

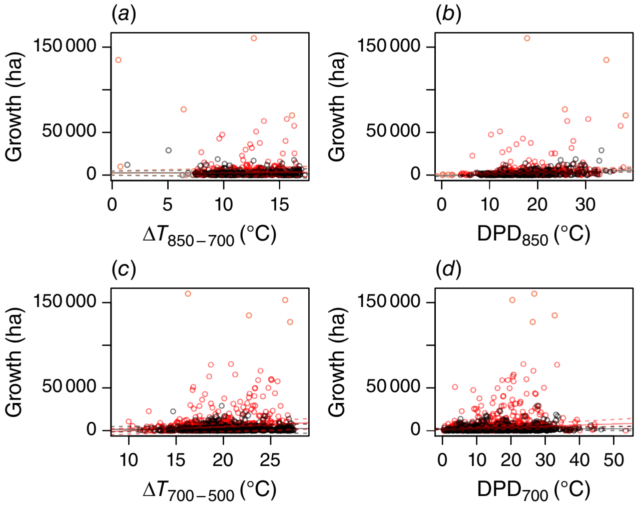

Fig. A3. Unscaled area growth response to mid-tropospheric weather measures aggregated for FOUS (red) and LFs (black): (*a*) $\Delta T_{850-700}$; (*b*) DPD_{850}; (*c*) $\Delta T_{700-500}$; and (*d*) DPD_{700}. Open circles indicate individual daily values for fire in each set. Solid lines are the best-estimate linear 80th quantile regression, dashed lines show the bounding envelopes of slope and intercept estimates provided by R software.

Table A1 shows how L_s growth on days when each weather measure was a high outlier compares with lifetime average growth for FOUS and LFs. (Results for growth measured as A are identical to those for A_s, shown in Table 2.) Outlier growth differs most markedly between the two fire sets for DPD_{850} and $\Delta T_{700-500}$. For the former, however, while fires in both sets grow more than average on high outlier days, it is LF growth that is greatest during outlier days. (Using A or A_s to measure growth, DPD_{850} outlier growth was not particularly notable.) For $\Delta T_{700-500}$, FOUS grew more than twice their lifetime average on outlier days, but LFs grow only 60% of their lifetime average. This pattern is similar to, but more extreme than what is seen when A or A_s is used to measure growth.

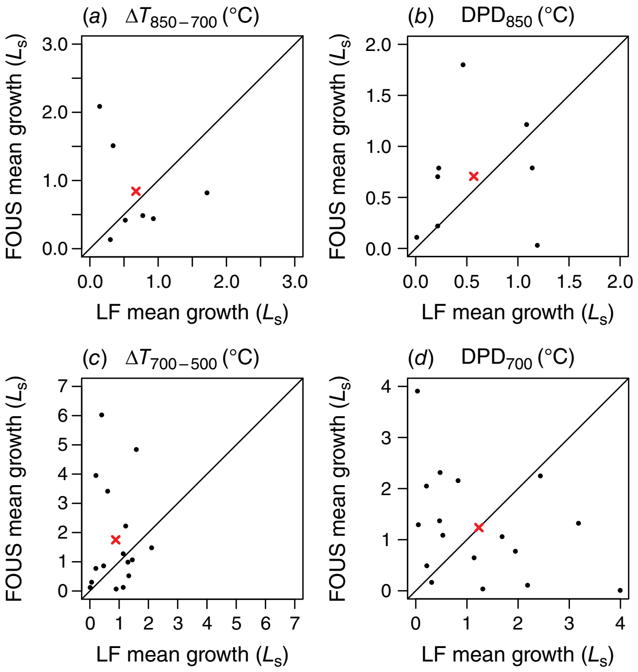

Fig. A4. As Fig. A1 but for scaled linear growth (L_s).

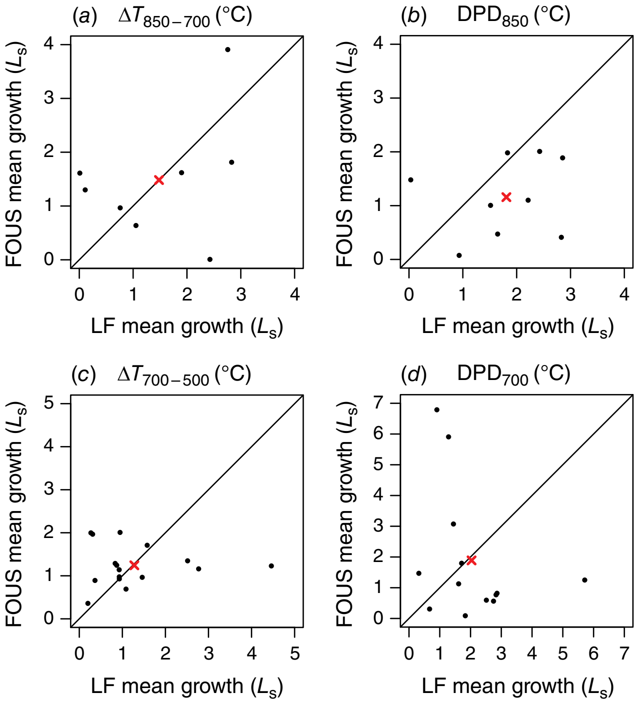

Fig. A5. As Fig. A2 but for scaled linear growth (L_s).

Wind change measures

FOUS area growth response to wind changes was greater than paired LF response for all three measures, and both middle and top quintile weather (Figs A7, A8). In both quintiles, LF growth response is comparable with lifetime average for all three wind change measures. FOUS growth response is more varied. For $\Delta\theta$ in middle quintile, growth response is above lifetime

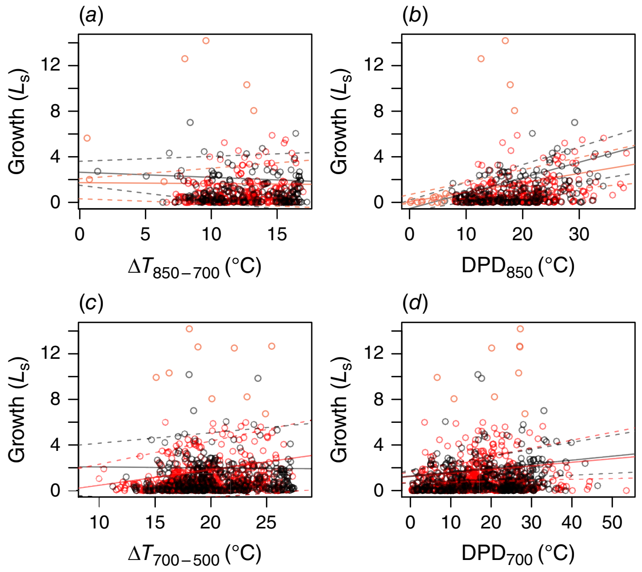

Fig. A6. As Fig. A3 but for scaled linear growth (L_s): (*a*) $\Delta T_{850-700}$; (*b*) DPD_{850}; (*c*) $\Delta T_{700-500}$; and (*d*) DPD_{700}.

Table A1. Ratio of L_s growth on high outlier days to lifetime-average growth across all fires in each set.

Variable	No. FOUS	No. LFs	FOUS ratio	LF ratio
DPD_{850}	2	2	1.91	3.43
$\Delta T_{850-700}$	3	2	1.96	1.21
DPD_{700}	6	4	2.89	2.57
$\Delta T_{700-500}$	5	2	2.20	0.60
$\Delta\theta$	3	6	0.41	1.13
$\lvert\Delta\theta\rvert$	8	4	0.00	0.00
ΔV	7	7	2.02	1.55

The number of fires with outliers for a given weather property is provided, as not every fire had outlier days for any given weather property.

average, but it is below average for the other weather measures. For upper quintiles, FOUS growth response is slightly above average for all three wind change measures. The scatter of (LF, FOUS) points also lies heavily on the FOUS side of the 1:1 line in both figures. Quantile regression (Fig. A9) on the aggregated data shows very little visual difference and near-zero slope.

Measuring growth using L_s (Figs A10, A11), middle quintile response to $\Delta\theta$ and ΔV is greater for FOUS than for LF, and exceeds lifetime average for the former. The numbers of pairs above and below the 1:1 line are similar. For top quintile $\Delta\theta$, growth response for FOUS and LF is comparable in terms of both point-scatter across the 1:1 line and the group centroid. Growth response to ΔV remains slightly greater for FOUS. Response to $|\Delta\theta|$ is comparable for LF and FOUS in both middle and top quintile $|\Delta\theta|$ ranges. Quantile regression plots for all three wind change measures (Fig. A12) shows little difference between LF and FOUS. Of the three measures, ΔV shows the greatest regression slope.

Fire growth on outlier days for the wind measures (Table 2 for growth measured as A or A_s, Table A1 for growth measured as L_s) shows little difference between the sets of fires for $\Delta\theta$ or $|\Delta\theta|$. For the latter, growth was effectively zero on the high outlier days. Growth on ΔV outlier days is greater for FOUS than for LFs, the difference being greater when measured using A or A_s than when using L_s.

Choice of growth measure – A, A_s, or L_s – does not change the results of this study for any weather measure except ΔV. The growth response of FOUS is comparable with that for LFs. For ΔV, there is little or no difference in growth response when measured as L_s. There is some difference (greater response for FOUS than LFs) at higher ΔV values when L_s is the growth measure, slightly more difference when A_s is the growth measure, and still greater response over a broader range of ΔV, when A is the measure.

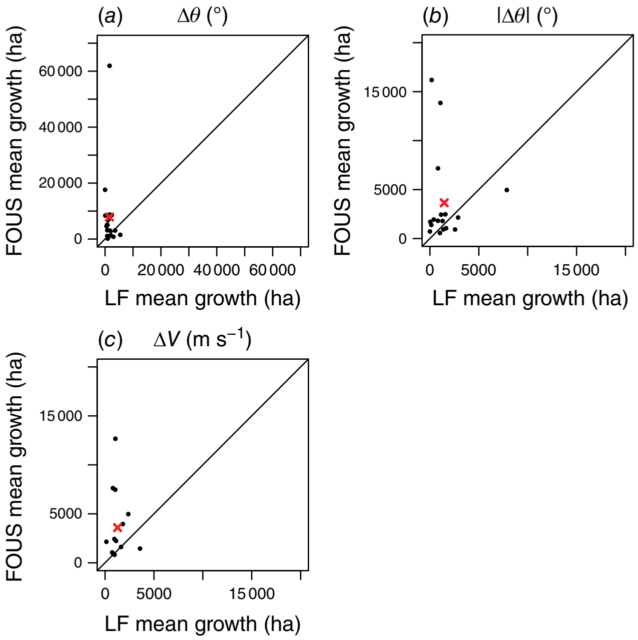

Fig. A7. Paired mean unscaled area growth (*A*, ha) response for pairwise third quintile (40th to 60th percentile) weather: (*a*) Δθ; (*b*) |Δθ|; and (*c*) ΔV. In each panel the (red) X indicates the mean growth response across all (LF, FOUS).

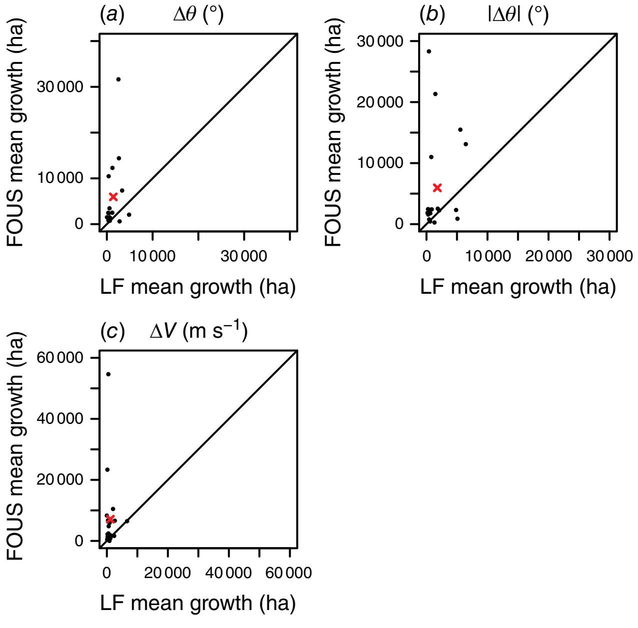

Fig. A8. As Fig. A7 but for pairwise fifth quintile (80th to 100th percentile) weather.

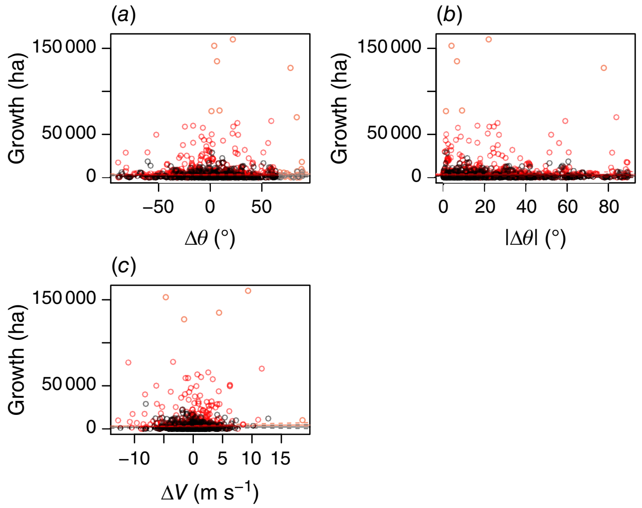

Fig. A9. Unscaled area growth response to wind change measures aggregated for FOUS (red) and LF (black): (*a*) $\Delta\theta$, (*b*) $|\Delta\theta|$, and (*c*) ΔV. Open circles indicate individual daily values for fire in each set. Solid lines are the best-estimate linear 80th quantile regression, dashed lines show the bounding envelopes of slope and intercept estimates provided by R software.

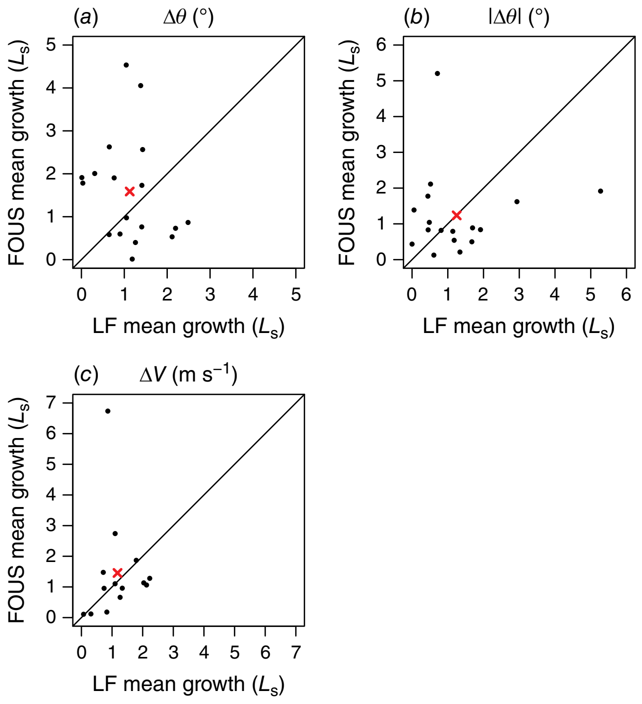

Fig. A10. As Fig. A7 but for scaled linear growth (L_s).

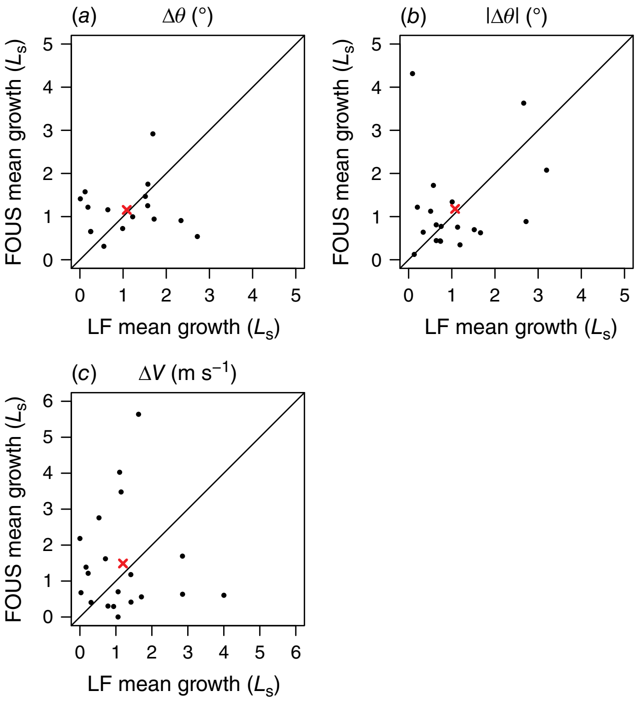

Fig. A11. As Fig. A10 but for top quintile growth response.

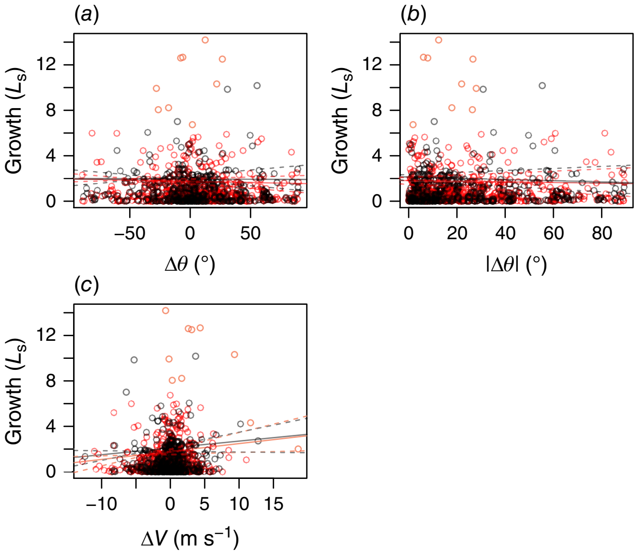

Fig. A12. As Fig. A9 but for scaled linear growth (L_s).