Determinants of fire intensity and severity in a mesic savanna of Africa

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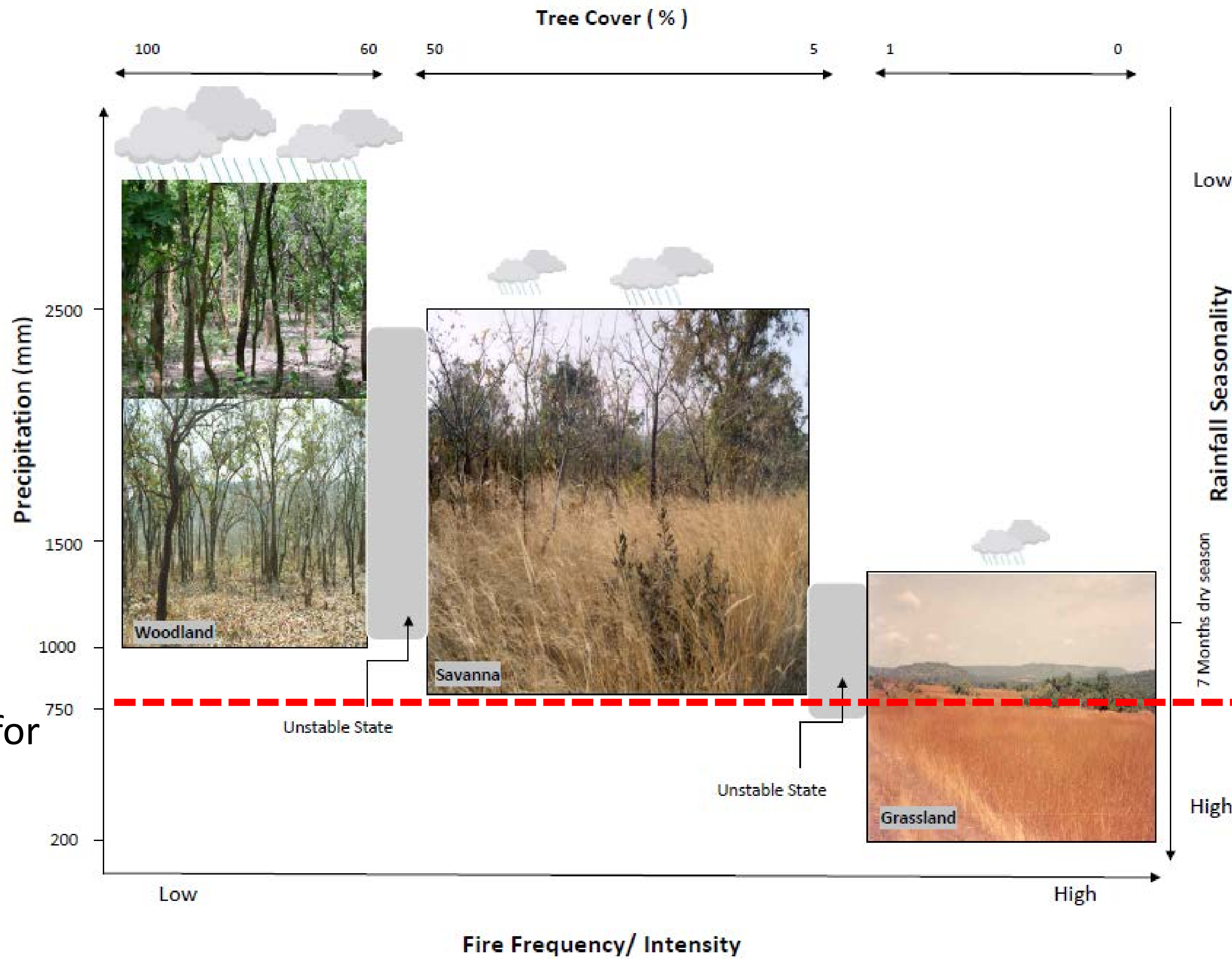
Fire-Driven (Mesic) Savanna Ecology Models

“Fire, which prevents trees from establishing, differentiates high and low tree cover, especially in areas with rainfall between 1000 mm and 2000 mm” (Staver et al 2011).



Sankaran 750 mm for Africa

Fire determined

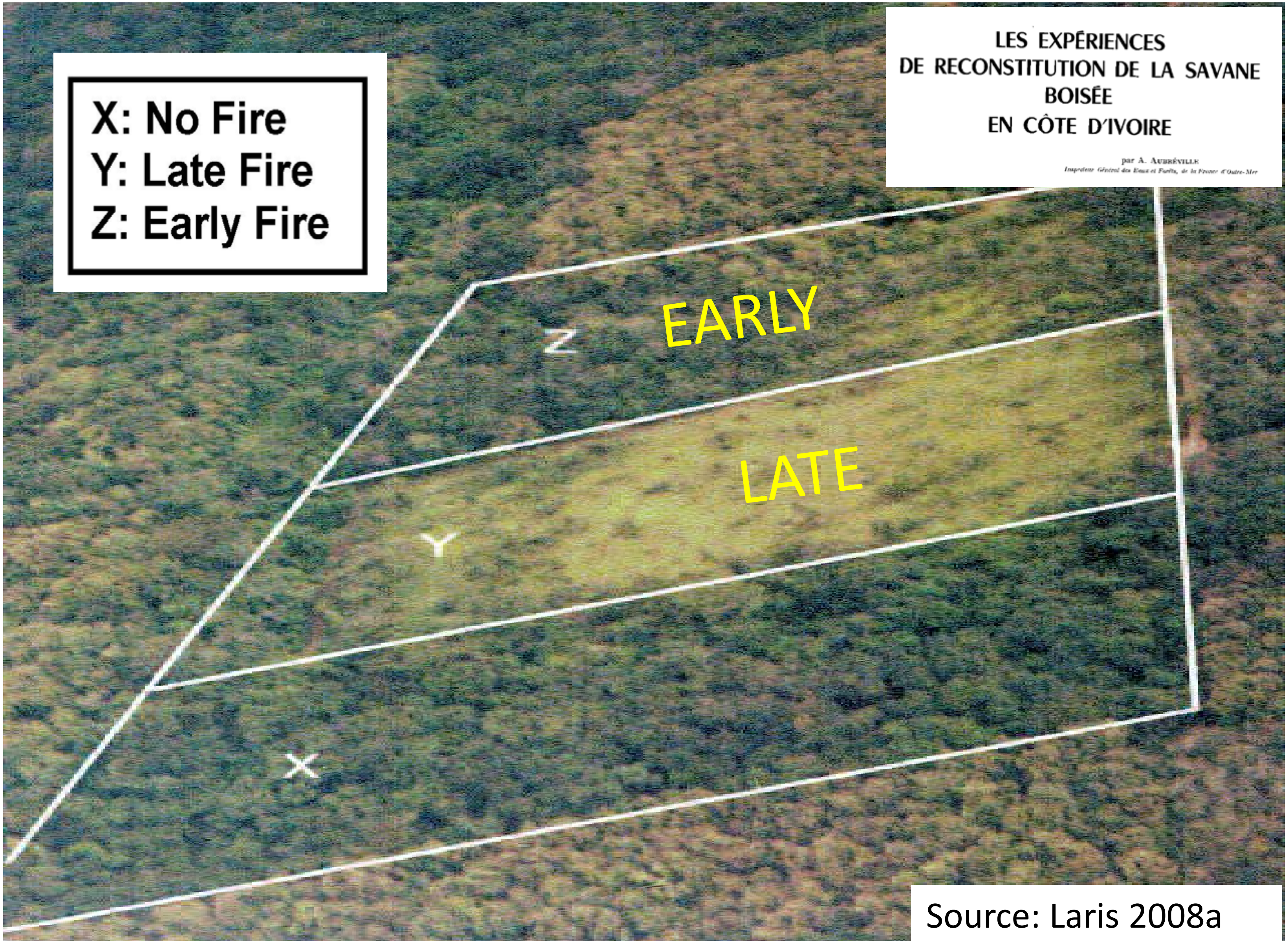
Precipitation determined

First Law of Savanna Fire Ecology

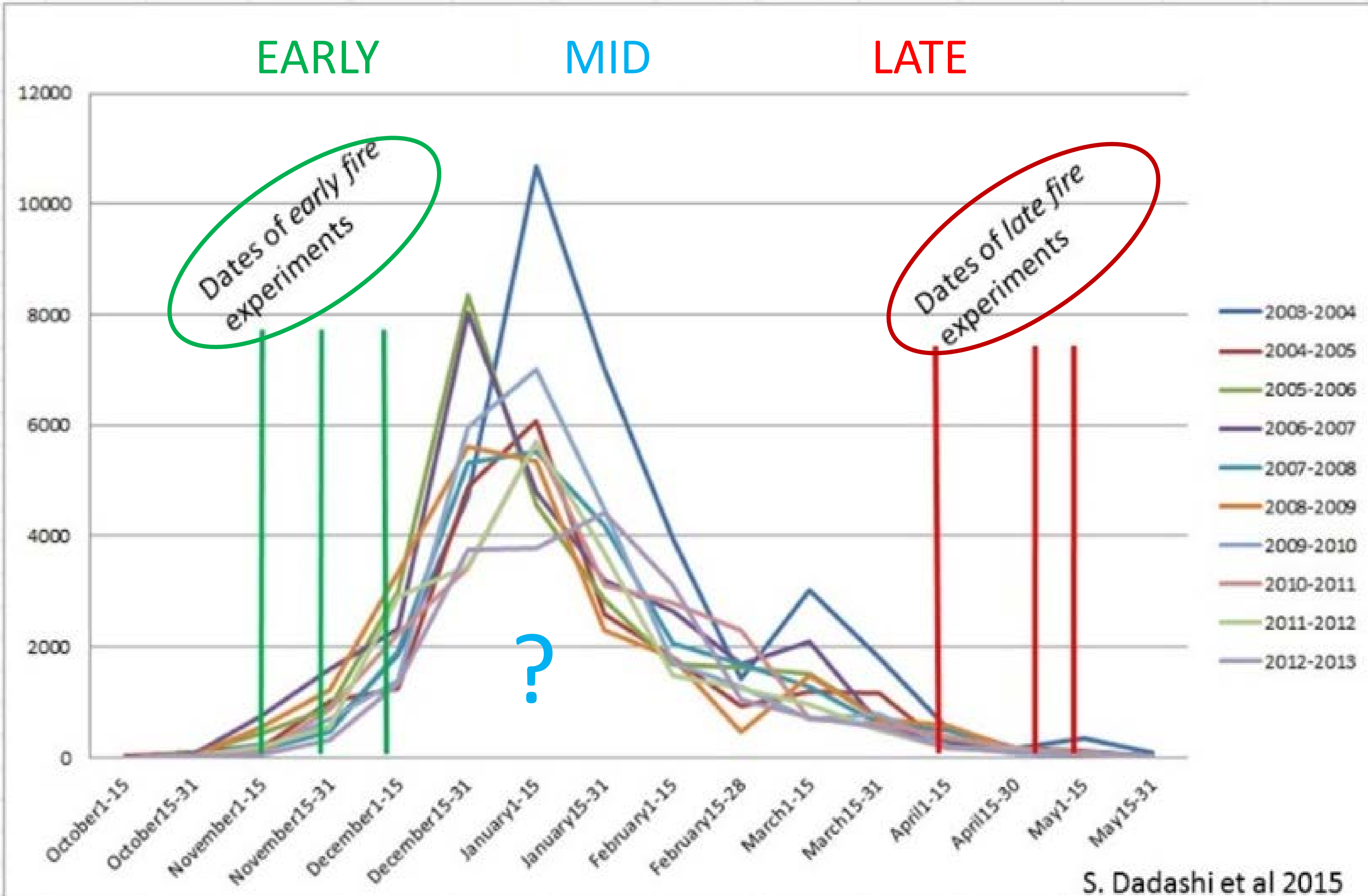
Fire regime determines vegetation (Tree) cover in a mesic savanna


Second Law of Savanna Fire Ecology
Late fires are **more intense** than early fires and thus more damaging to trees (especially juveniles).
Timing of fire => fire intensity, severity & ecosystem response
Laris et al 2016

Aubréville's burning experiments: timing matters!



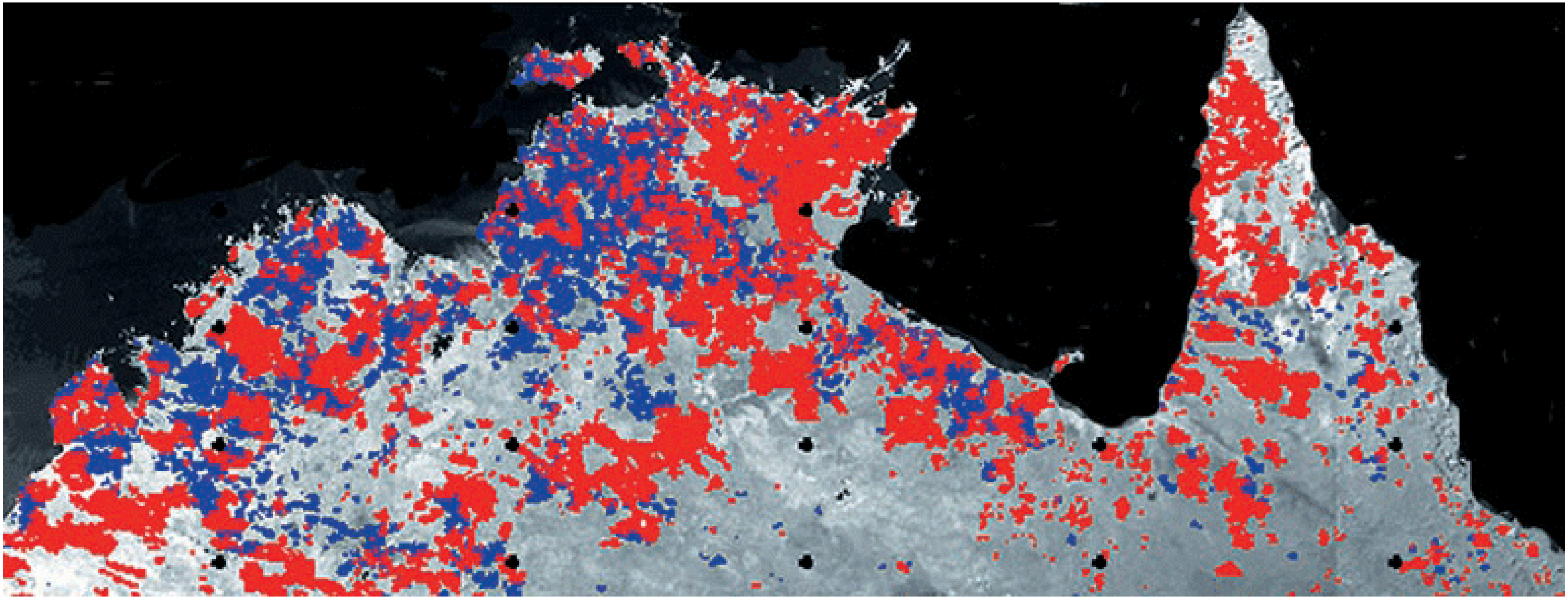
Fire Season* and *Historic* Experiment Dates



* Based on analysis of 10 years of MODIS active fire data

Representing fire: the Early/Late Dichotomy

A dominant view of savanna fires



The Australian Fire Regime: Blue - fires before June 30; Red - fires after June 30. Source: WA DLI

The predominant view of fire is Early/Late: IPCC…emissions decrease by season

Influence of timing and spatial extent of savanna fires in southern Africa on atmospheric emissions

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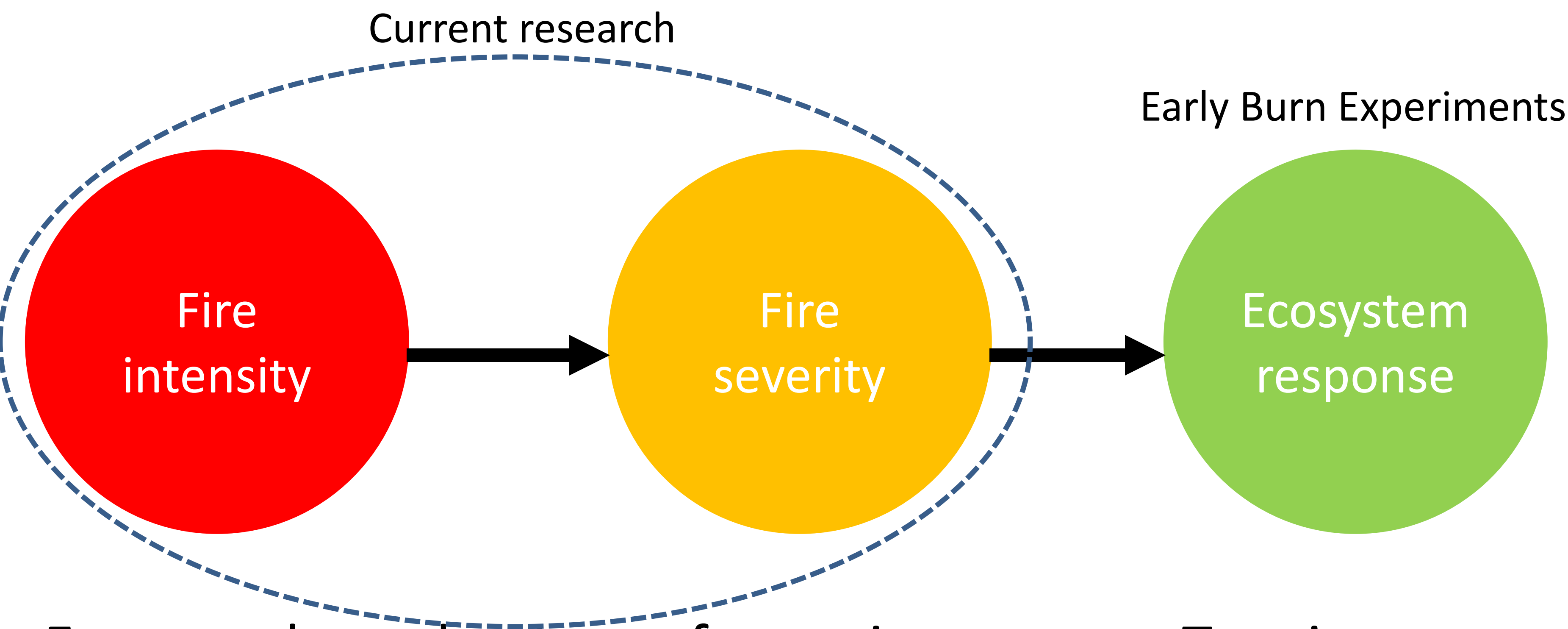
Since the emission factor for CH_4 can decrease by 50–75% as the burning season progresses, it is strongly suggested that each inventory agency collect seasonal data on the fraction of savanna area burned, the aboveground biomass density, and the fraction of aboveground biomass burned in each savanna ecosystem from the early dry season to the late dry season.

IPCC 2000 (chap. 4, §A.1.1.3, p. 4.87)

Fire intensity, severity and ecosystem response: Jon Keeley 2009



Energy released (biomass + speed)

Loss of organic matter (observed biomass lost)

Tree impacts (tree survival /top-kill)


Sample fire plot from Faradiele study area
Leaves remaining on small juvenile trees indicate a **low intensity fire** for a February--late season--burn)

Problem: Why are late season fires worse?

West (1965) theorized reasons why fire seasonality matters:

A) From the perspective of trees

B) From the perspective of the grasses (fuel)

C) From the perspective of the weather

West (1965) theorized reasons why fire seasonality matters (trees)

(A) From the perspective of trees (in the later months of the dry season):

(i) plants have higher temperatures and are thus heat stressed;
(ii) most trees have produced new leaves and thus, reserves are depleted;
(iii) there is less bark protection because moisture is low;
(iv) new leaves are susceptible to heat damage and further loss of leaves saps trees of depleted reserves.

West (1965) theorized reasons why fire seasonality matters (fuel & weather)

B) the perspective of the grasses (fuel)

- lower fuel moisture later in the dry season
- taller, often perennial grasses, were set to fire later

C) From the perspective of the weather

- later dry season tends to have higher temperatures and winds as well as lower humidity, which result in higher fire intensity

Study Objectives and Questions

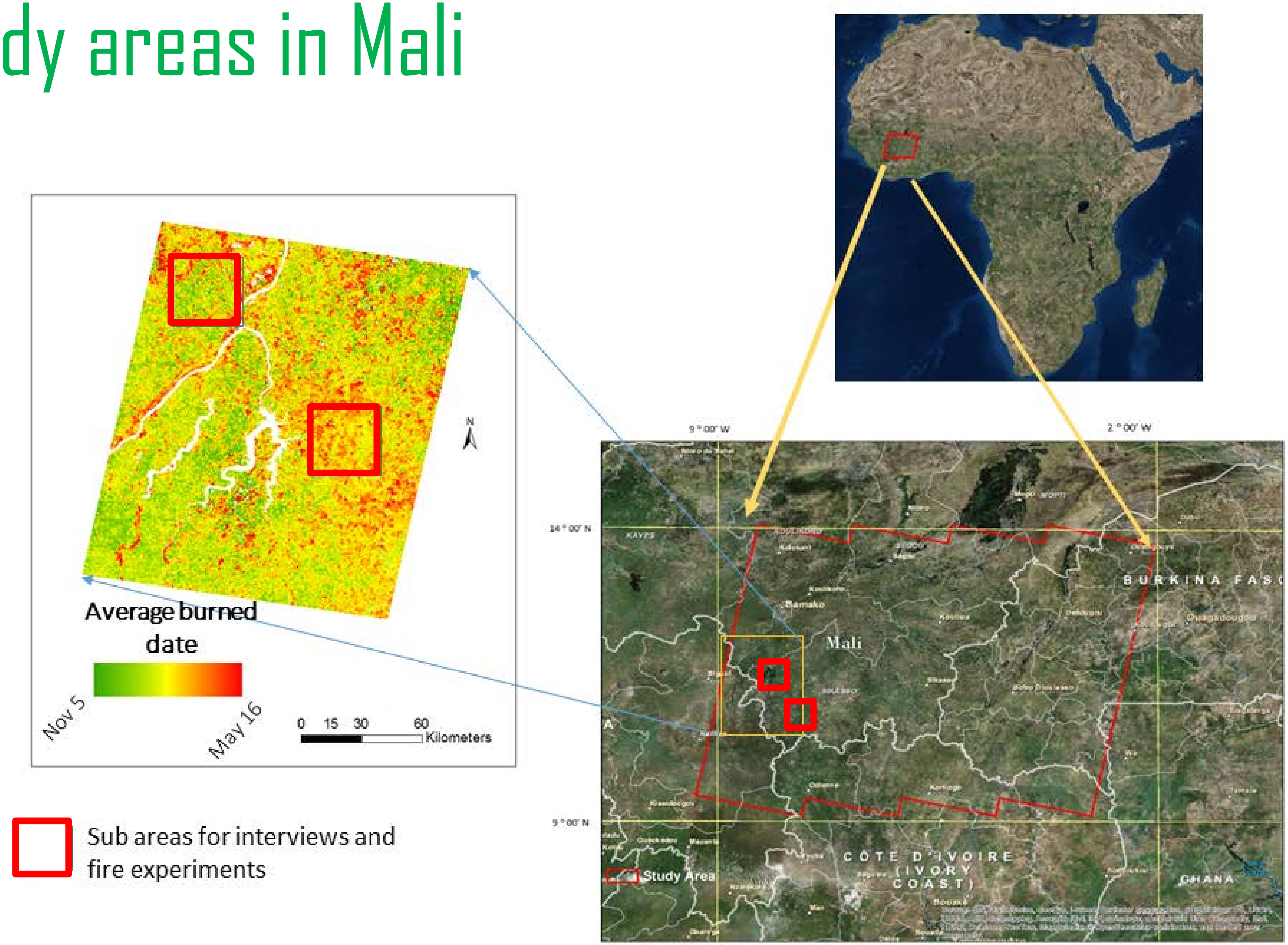
What factors determine fire intensity and severity in a West African savanna?

(i) Does seasonality (timing) explain fire intensity or severity?
(ii) Do weather conditions influence fire intensity or severity?
(iii) Does grass species (annual vs perennial) effect fire intensity or severity?
(iv) Does fire type (wind direction) determine fire intensity?
(v) Does the intensity from a humanized fire regime vary by from that of randomly set fires?

Study Approach

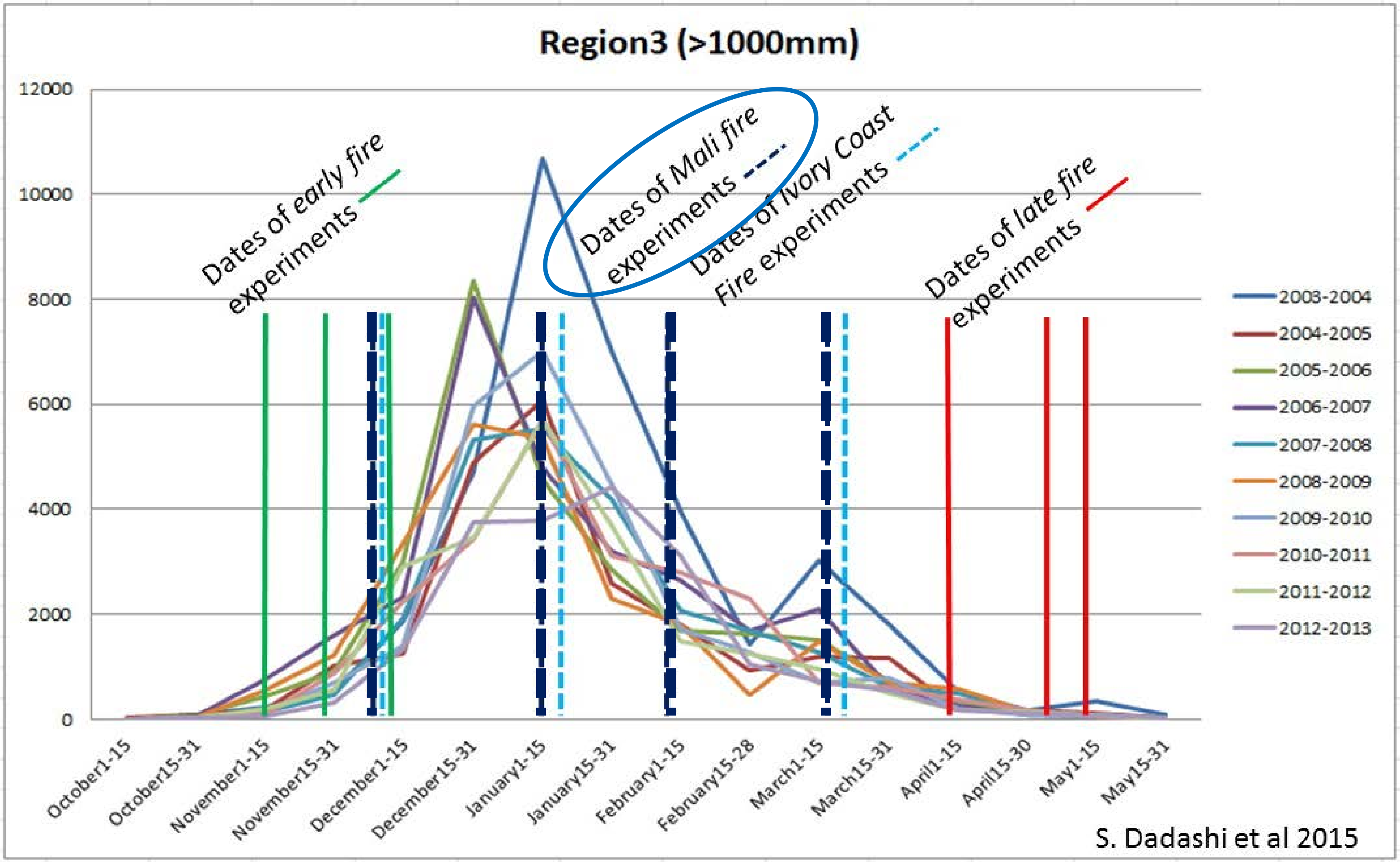
- Study areas in two zones: Tabou with 900< precip <1000mm and Faradiele with 1000<precip<1100mm
- Conduct 100+ experimental fires during 3 seasons: early, middle and late.
- Two methods of determining fire timing (local and seasonal)
- Record data on biomass type and weight, weather conditions, fire speed, time of day, scorch height and % biomass consumed (severity) and calculate fire intensity.
- Estimate impacts on tree cover

Study areas in Mali

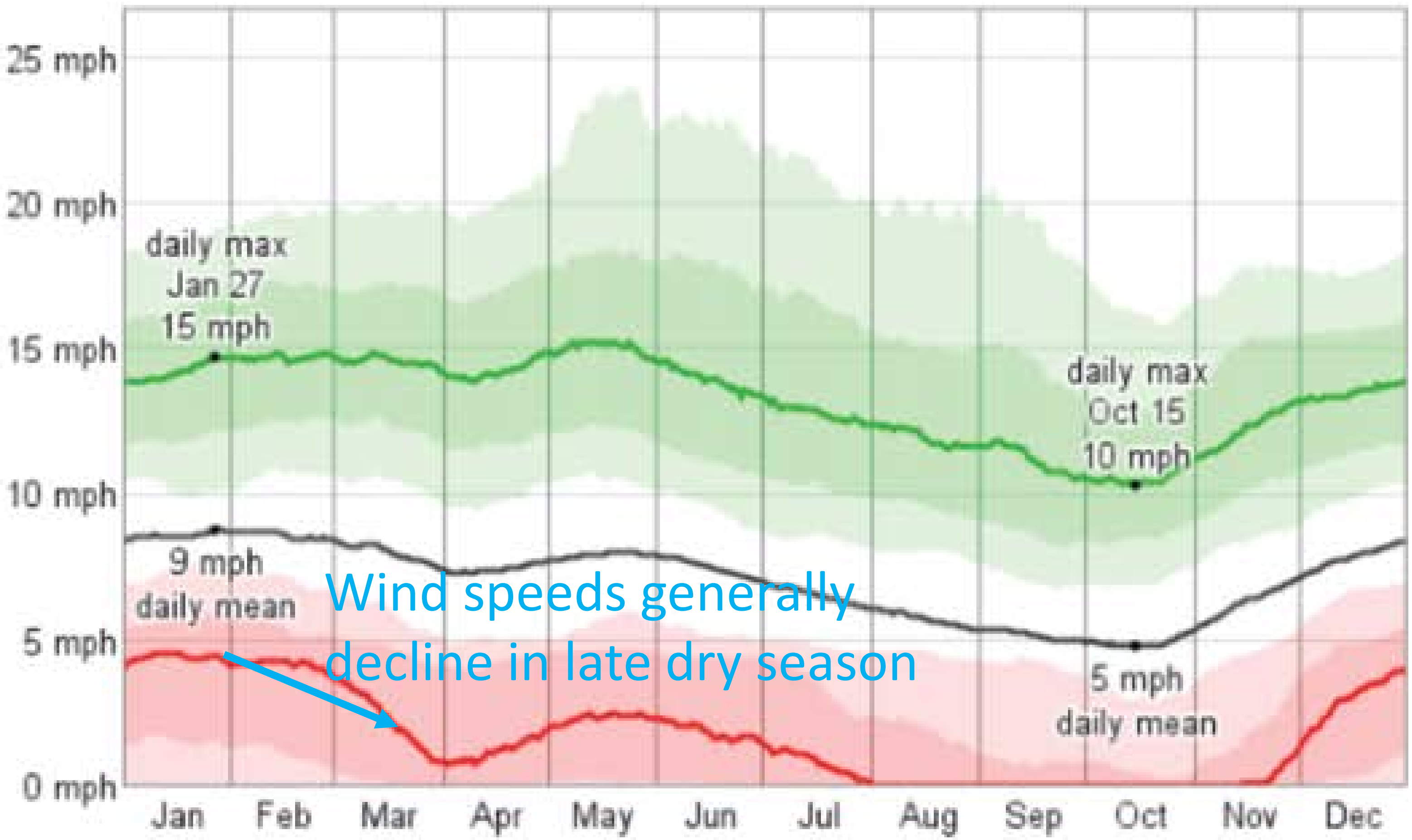


Dry (fire) season from November-May

Dates of our fire experiments and annual fire timing and frequency (historical burning experiment dates shown for comparison)

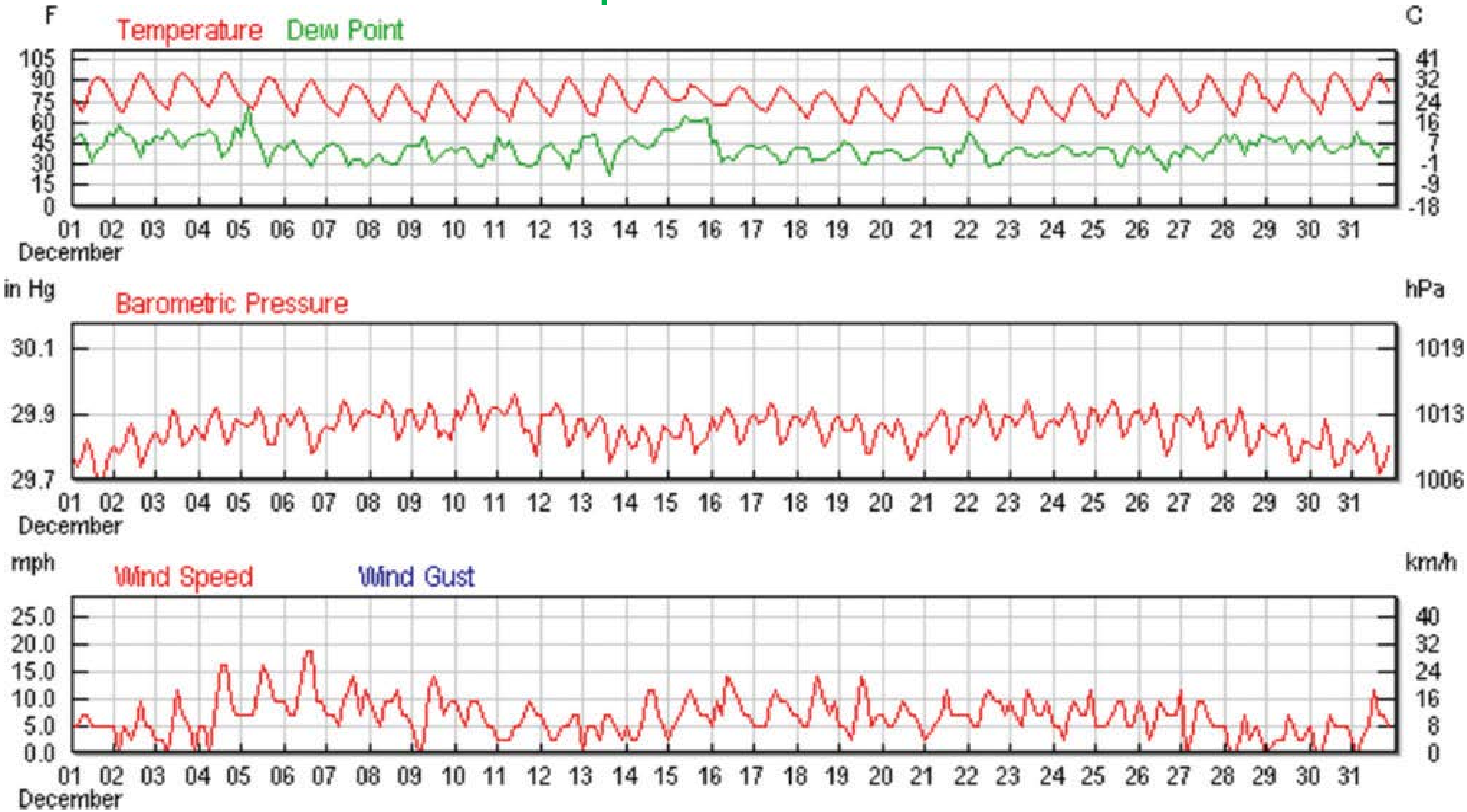


Average wind speed peak in midseason (January--February), then decline *



* Note that Bamako Airport has slightly elevated wind speeds, but the seasonal pattern reflects the region

The wind fluctuation by **time of day** is far greater than by season, winds *peak* in mornings, while T and H peak in mid-afternoon



Fire-line Intensity Calculation

Byram's Fireline Intensity (Energy released) :

1. The heat of combustion (from Williams et al 1998)

2. The amount of fuel consumed (measure in field)

3. The rate of spread (measure in field)

The formula to compute fireline intensity is: $I = Hwr$

where I is Byram's fireline intensity (kWm^{-1}), H is the net low heat of combustion ($kJ\ kg^{-1}$), w is the fuel consumed in the active flame front ($kg\ m^{-2}$), and r is the linear rate of fire spread ($m\ sec^{-1}$). The heat of combustion (H) was selected following Williams, Gill, and Moore (1998) with 20,000 $kJ\ kg^{-1}$ as an appropriate value for savanna fires.

A little fire science: flaming front for head fire

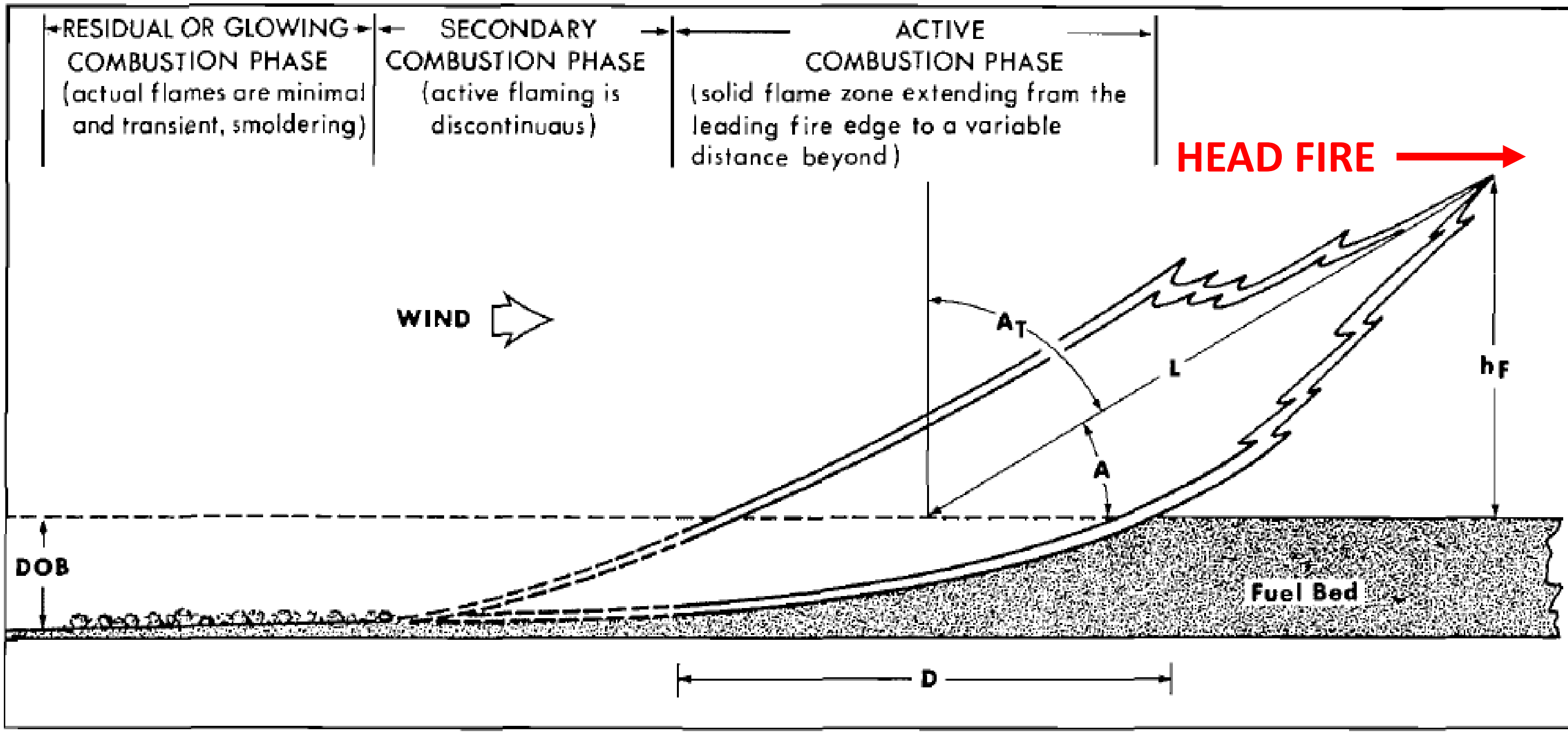
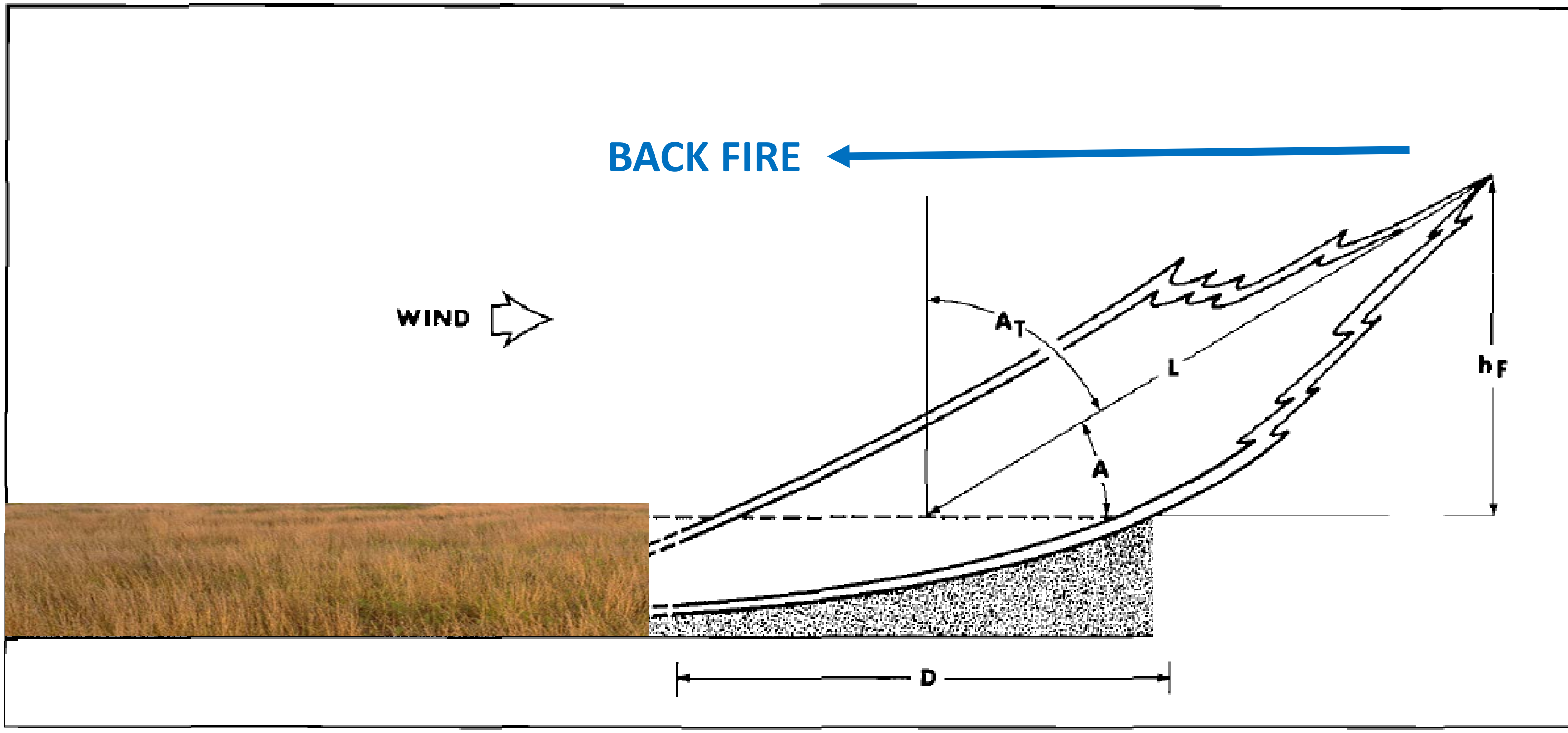


FIG. 1. Cross section of a stylized surface head fire on level terrain illustrating the energy or heat-release stages during and following passage of the flame front, flame length (L), flame height (h_F), flame angle (A), flame tilt angle (A_T), horizontal flame depth (D), and the resulting depth of burn (DOB).

A little fire science: flaming front for back fire



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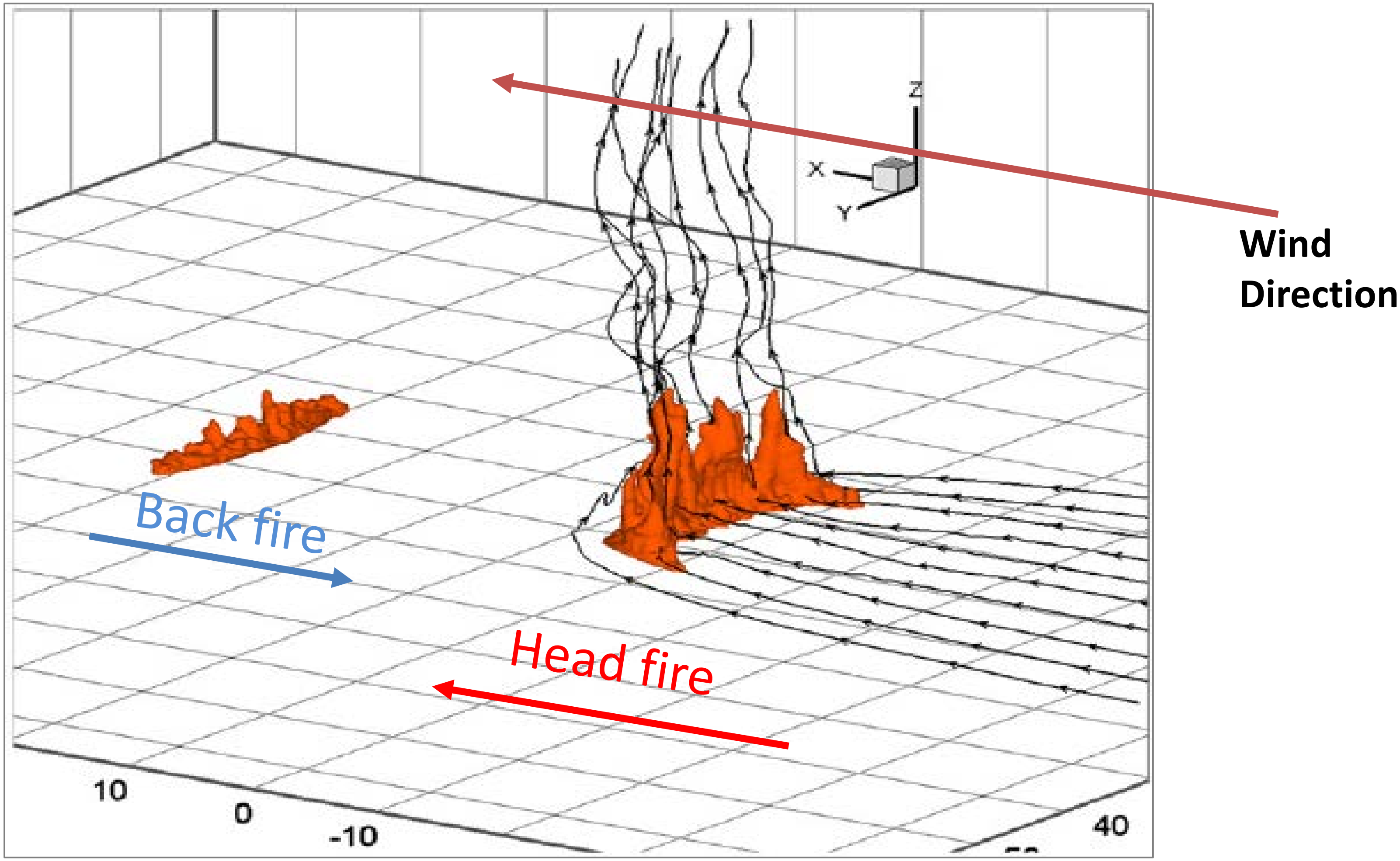
Schematic of intensity of flame for head and back fire: head fire moves faster, w/taller flames



https://www.researchgate.net/publication/257230525_Numerical_study_of_the_effect_of_fuel_moisture_content_FMC_upon_the_propagation_of_a_surface_fire_on_a_flat_terrain/figures?lo=1


RESULTS: What do field observations tell us?

Head fire VIDEO

Wind approximately 2.5 m/s

Note : Time

Back fire VIDEO

Temp = 40 C

Time = 1:20

RESULTS: Fire-line Intensity Values

Intensity ranged from 24.69 to 1395.36 kWm^{-1} for all plots*
Major distinction between head and back fire intensity values

- Mean head fire Intensity was 336.26 kWm^{-1}.
- Mean back fire Intensity was 124.24 kWm^{-1}.

Type of fire	n	Mean	Minimum	Maximum
Head	40	336.26	48.52	1395.36
Back	43	124.24	24.69	476.94

* Intensity values might be slightly lower given the small size of the plots burned and time it takes to develop the burning fire front.

RESULTS Fire Intensity by Season: Correlates for back fires but *not* head fires

Back fires

Correlation between season and intensity

Table 1. Subset of correlation matrix with **Head** fires in gold and **Back** fires in blue. Darker shades indicate significance of 0.05 or less.

		Season	Day Timing	Biomass Dry (t/ha)	Wind Speed (m/s)	Grass Biomass %	Humidity	Ambient Temp	Grass by Ht	Annual Perenial	Biom Load (t/ha)	Flame Height (m)	Visual Efficiency	Biomass Consumed %	Fire Speed (m/s)	Intensity
Season	Pearson Correlation	1	0.001	0.041	-0.071	-0.174	$-.570^{**}$	$.356^{*}$	0.066	0.069	-0.004	$.371^{*}$	$.498^{**}$	0.253	$.573^{**}$	$.488^{**}$
	Sig. (2-tailed)		0.996	0.792	0.653	0.264	0.000	0.019	0.674	0.662	0.978	0.014	0.001	0.102	0.000	0.001
	N	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43
Intensity	Pearson Correlation	0.089	0.005	$.668^{**}$	0.222	0.243	-0.131	0.128	-0.162	-0.134	$.555^{**}$	$.420^{**}$	$.367^{*}$	0.231	$.871^{**}$	1
	Sig. (2-tailed)	0.584	0.978	0.000	0.169	0.131	0.420	0.432	0.319	0.408	0.000	0.007	0.020	0.152	0.000	
	N	40	40	40	40	40	40	40	40	40	40	40	40	40	40	43

Head fires

No correlation between season and intensity

R. Jacobs

RESULTS Intensity correlates with fire speed, biomass, burn efficiency (severity), scorch height

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	N	40	40	40	40	40	40	40	40	40	40	40	40	40	40	43

For back fires only, ambient air temperature and humidity correlate with intensity as well.

Results

- Weather (R&H) only correlate with intensity of backfires and wind speed does not (surprising).
- Biomass consumed (dry and total) and fire speed correlate with intensity (as expected)
- **Scorch height,** an accepted metric for estimating fire intensity, was significantly correlated with Intensity in both head and back fires (expected).

Yay !

Range of variables in all fires

Variable	Mean ± Std Dev	Minimum	Maximum
Fuel load (kg/m^2)	0.46 ± 0.16	0.15	0.99
Fuel moisture (%)	0.07 ± 0.14	0	0.34
Air temperature (C^0)	33.3 ± 3.79	22.1	41.7
Relative humidity (%)	24.0 ± 7.39	10.5	41.3
Wind speed (m/s)	1.18 ± 0.59	0.2	2.9
Fire intensity (kJ/m/s)	226.42 ± 248.15	24.69	1395.36

Low variation in wind speed 0.2—2.9 m/s:

Considered a light breeze

Head fire regression model statistics. *No significant models* were created.

Model	R	R^2_{adj}	F	Sig F	Valid
Enter	.501	.115	1.848	.120	No
Backward	.421	.109	2.589	.068	No
Forward	N/A	N/A	N/A	N/A	No

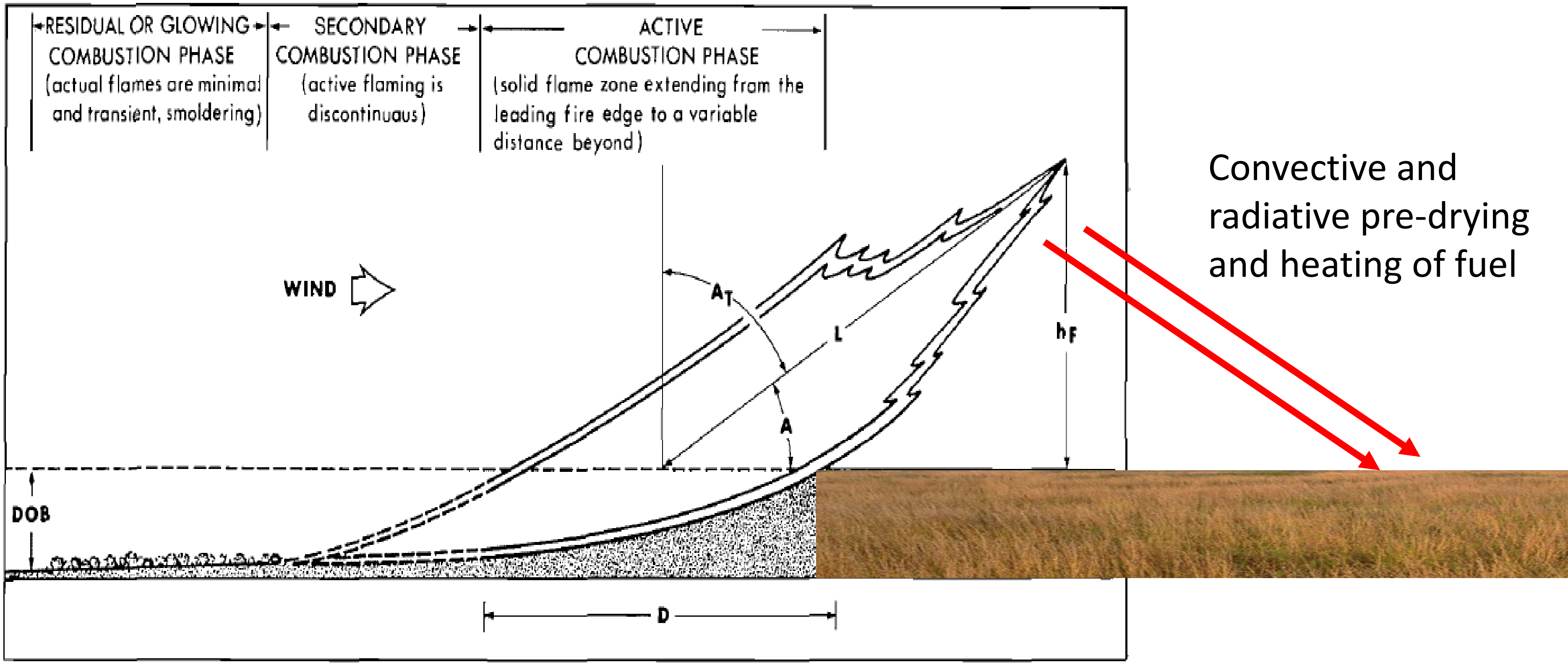
Indeed, **head fire intensity is not explained** by any common variables to do with weather, season or grass type. Head fire intensity is unpredictable (Trollope found this as well)

Back fire regression model statistics. Season and grass biomass % best explain fire intensity

Model	R	R^2_{adj}	F	Sig F	Valid	Explanatory Variable
Enter	.652	.290	3.143	.009	Yes	Season
Backward	.560	.279	9.137	.001	Yes	Season, Grass Biomass %
Forward	.560	.279	9.137	.001	Yes	Season, Grass Biomass %

Note that "grass biomass %" is the value for the percentage of all biomass consumed that is **grasses as opposed to leaf** matter. We know that leaf litter increases over time during the dry season.

Back to basics: A head fire preheats and dries grasses, thus season (fuel moisture) not important



Convective and radiative pre-drying and heating of fuel

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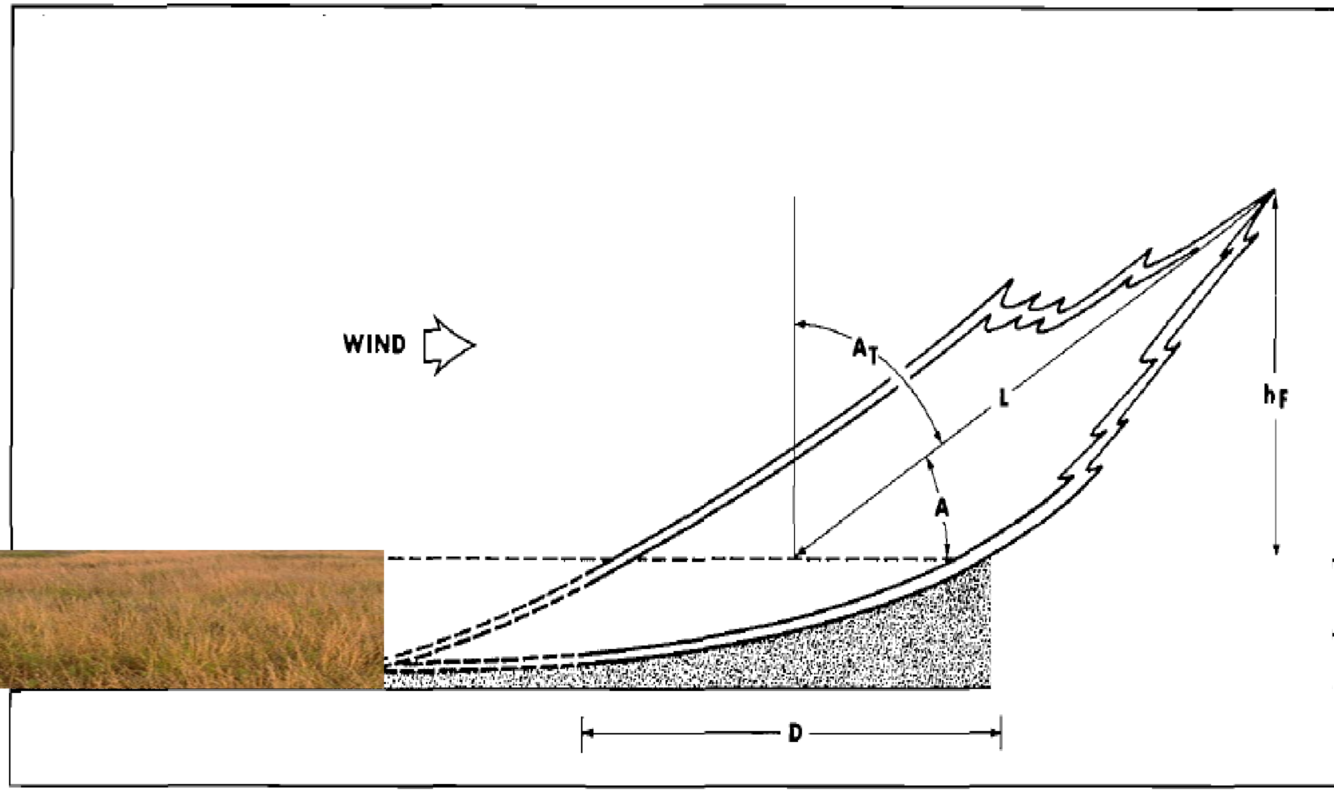
Back fire has little effect on preheating or drying grasses, season does matter

Little convective and little radiative pre-drying, thus moisture level of fuel matters.



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Digging Deeper:
2 Methods of fire research

- A. Fire timing *a function of land manager practice* (fires set to grasses at moment they are dry enough to burn)

- B. Fire timing ***not*** a function of land managers (fires set to all vegetation types for all seasons)

Fire timing and grass type: Head fires

- With head fires there is no correlation between fire intensity and seasonality for either type A or type B

Does not matter whether grasses are set on fire when moist, almost dry or very dry or randomly.

Fire timing and grass type: Back fires

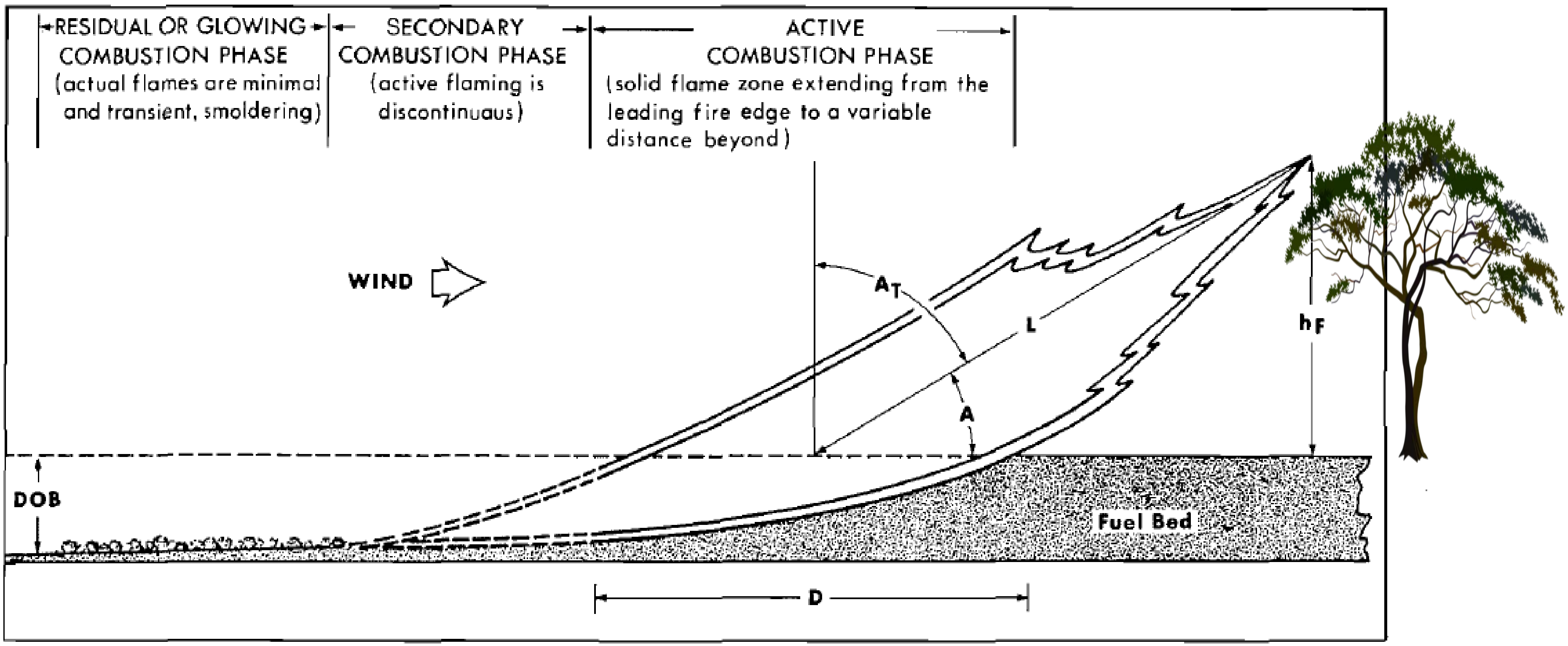
- With back fires there is **no correlation** between fire intensity and seasonality for type **A—fires set by land managers according to grass type**

- With back fires there is a **correlation** between fire intensity and seasonality for type **B—fires set for all grasses and all seasons**

Yay !

Thus for back fires, ***season does matter*** when grasses are set on fire at different times of year or randomly (i.e., different levels of dryness) not when they are set systematically.

What about the Trees?: Are intense head fires more damaging to trees?



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What kind of fires do people intentionally set in Mali?

Interview results find that:

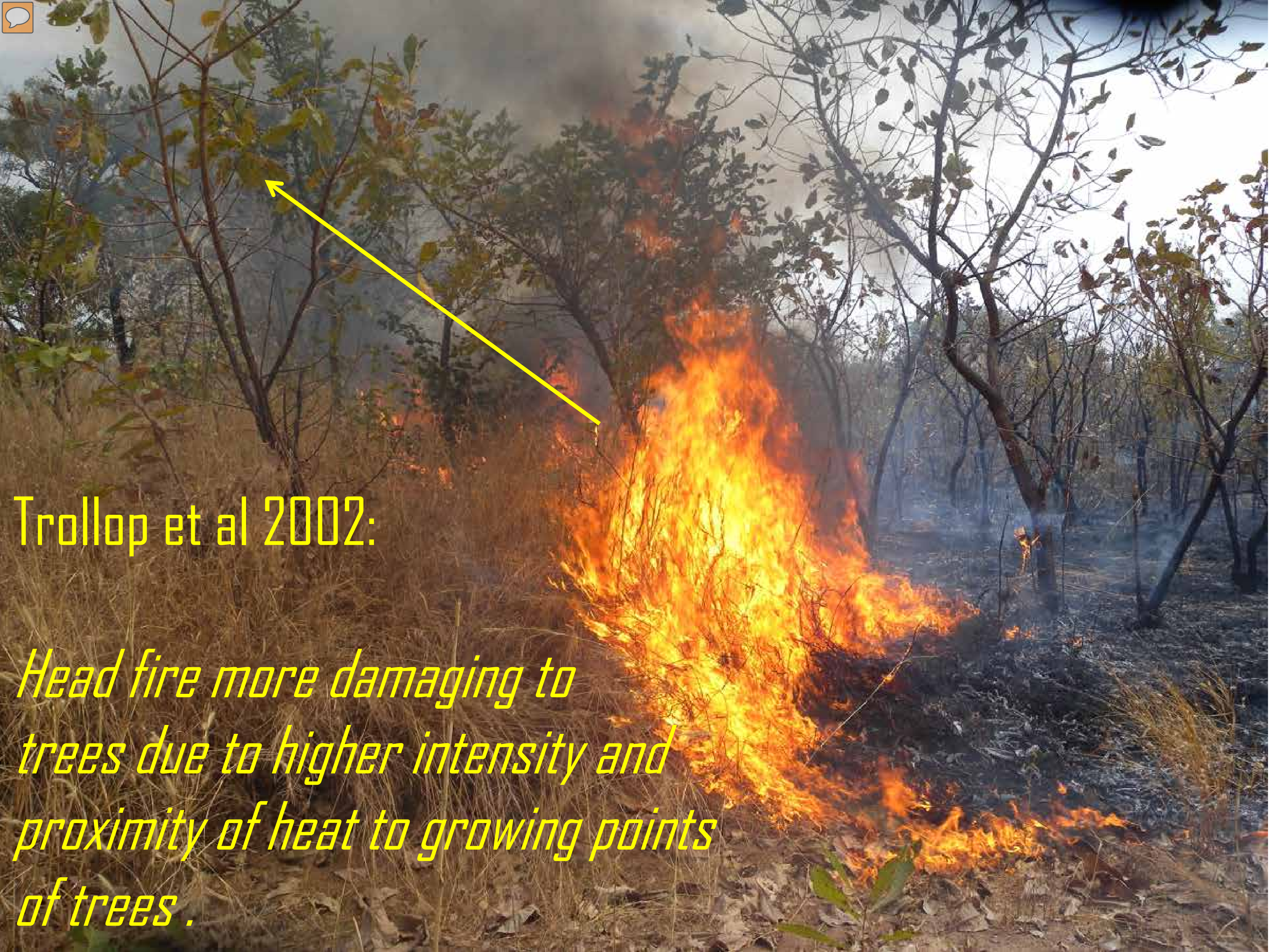
- Most fires are set in **early to mid** fire season
- People overwhelmingly set **back-fires** when they purposefully set fires
- Afternoon is the preferred time for setting fires because winds are dropping and humidity rising, thus, fires are easier to control and **tend to burn themselves out** at night.
- People set fires to grasses purposefully when they are still slightly moist, but **just dry enough** to burn.

Laris et al 2002, 2011, 2016

What kind of fire *intensity* results when people intentionally set fires in Mali?

Our results suggest that:

- Backfires are lower intensity
- Afternoon (lower temperature, lower wind and higher humidity) back-fires are lower intensity
- By setting fires according to grass type (grass dryness) **intensity does not vary by season!!**


Trollop et al 2002:
Head fire more damaging to trees due to higher intensity and proximity of heat to growing points of trees .

Summary

- Fire intensity does not correlate with fire season ***except*** for the case of back-fires.
- ***Randomly set*** back fire intensity correlates with season, biomass, scorch height, temperature, humidity & severity
- Head fires only correlate with biomass and scorch height and speed
- When the human factor is considered, there is **no correlation** between season and intensity for either head or backfires
- **Fire direction** and **fuel type** (grass species and leaf litter) are major unknowns in the data. Yet these factors matter!


Future Study: Leaf Litter increases as dry season progresses...more critical than grass type and moisture content?
Think about burn efficiency and emissions!
Late January:
Mid-season

Conclusions

- Analysis of over 100 fires finds that fire intensity and season do not correlate for most fire regimes.
- It is likely that head fires are more damaging to trees, but there is very little data on *actual fires* from West Africa
- The impact of fires on tree survival and top-kill needs to be empirically derived (Keeley) …tree phenology is likely critical.
- Future research: How does **tree stress** and phenology impact juvenile tree ability to survive a fire?

Thanks to all of those people in Mali and elsewhere who made the research possible

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