Estimating fire intensity, combustion completeness and greenhouse gas emissions for a *working* savanna landscape in Mali, West Africa.

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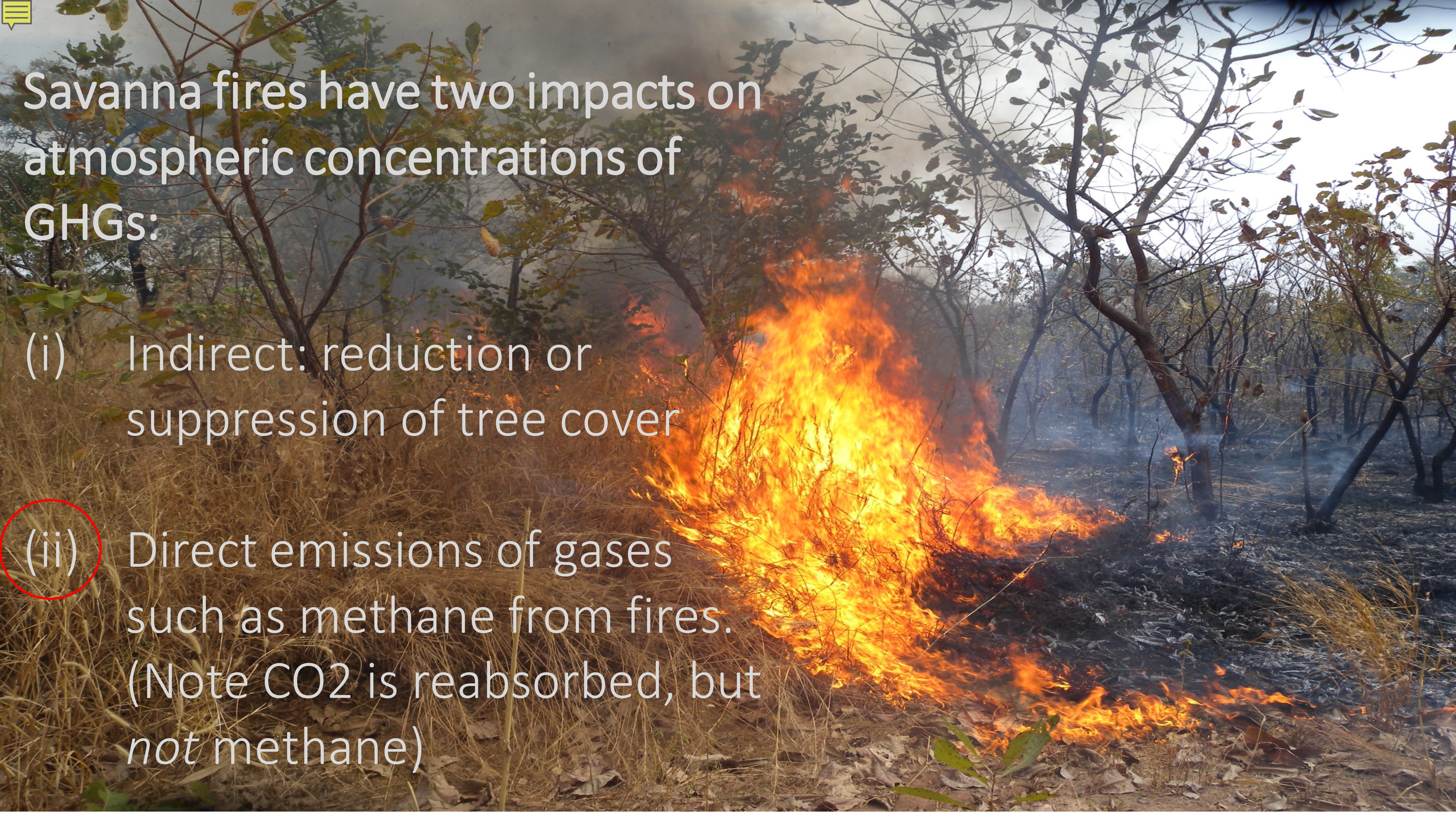

Savanna fires have two impacts on atmospheric concentrations of GHGs:

(i) Indirect: reduction or suppression of tree cover

(ii) Direct emissions of gases such as methane from fires. (Note CO2 is reabsorbed, but *not* methane)

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ARTICLE

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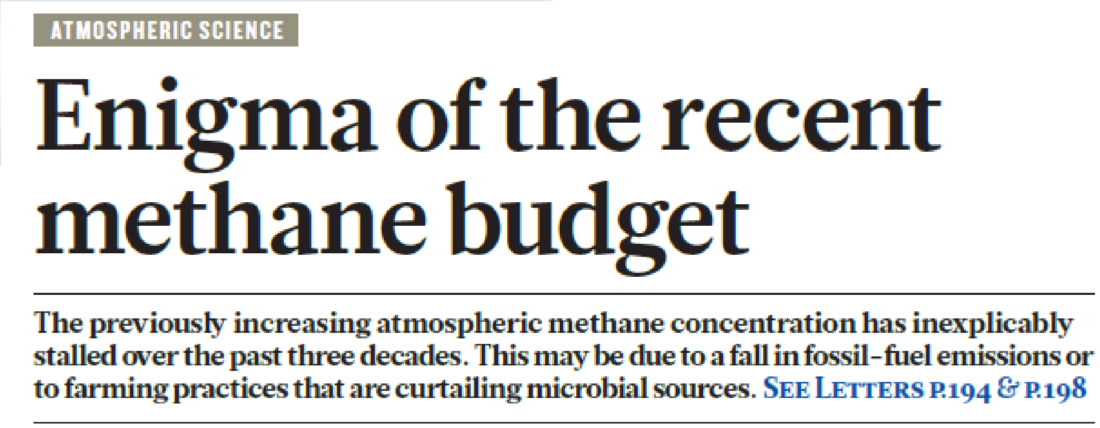
Reduced biomass burning emissions reconcile conflicting estimates of the post-2006 atmospheric methane budget

John R. Worden[1], A. Anthony Bloom[1], Sudhanshu Pandey[2,3], Zhe Jiang[1,4], Helen M. Worden[4], Thomas W. Walker[1], Sander Houweling[2,3,5] & Thomas Röckmann[2]



ATMOSPHERIC SCIENCE

Enigma of the recent methane budget

The previously increasing atmospheric methane concentration has inexplicably stalled over the past three decades. This may be due to a fall in fossil-fuel emissions or to farming practices that are curtailing microbial sources. SEE LETTERS P.194 & P.198

By one estimate savanna fires contribute 62% (4.92 PgCO2-e yr−1) of gross global mean fire emissions (Lipsett-Moore et al 2019).

High uncertainty in the data: 34-69% (Worden et al)

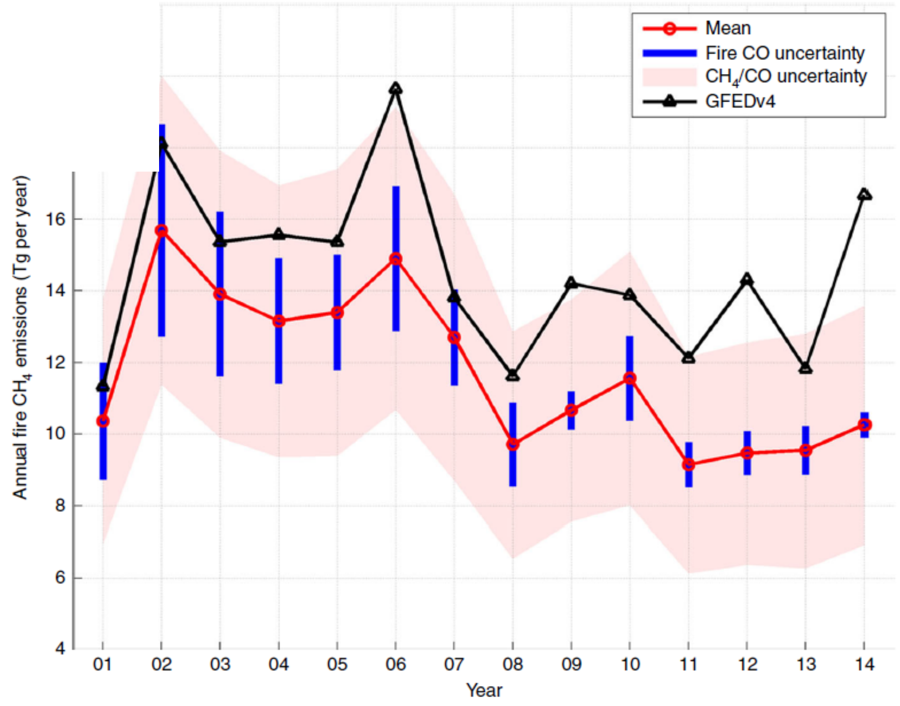


Fig. 1 Trend of methane emissions from biomass burning. Expected methane emissions from fires based on the Global Fire Emissions Database (black) and the CO emissions plus CH_4/CO ratios shown here (red). The range of uncertainties in blue is due to the calculated errors from the CO emissions estimate and the shaded red describes the range of error from uncertainties in the CH_4/CO emission factors

POLICY:

Increase **early** and reduce **late** burning to **reduce** GHG emissions by (69.1 MtCO2-e/yr), (Lipsett-Moore et al 2019)

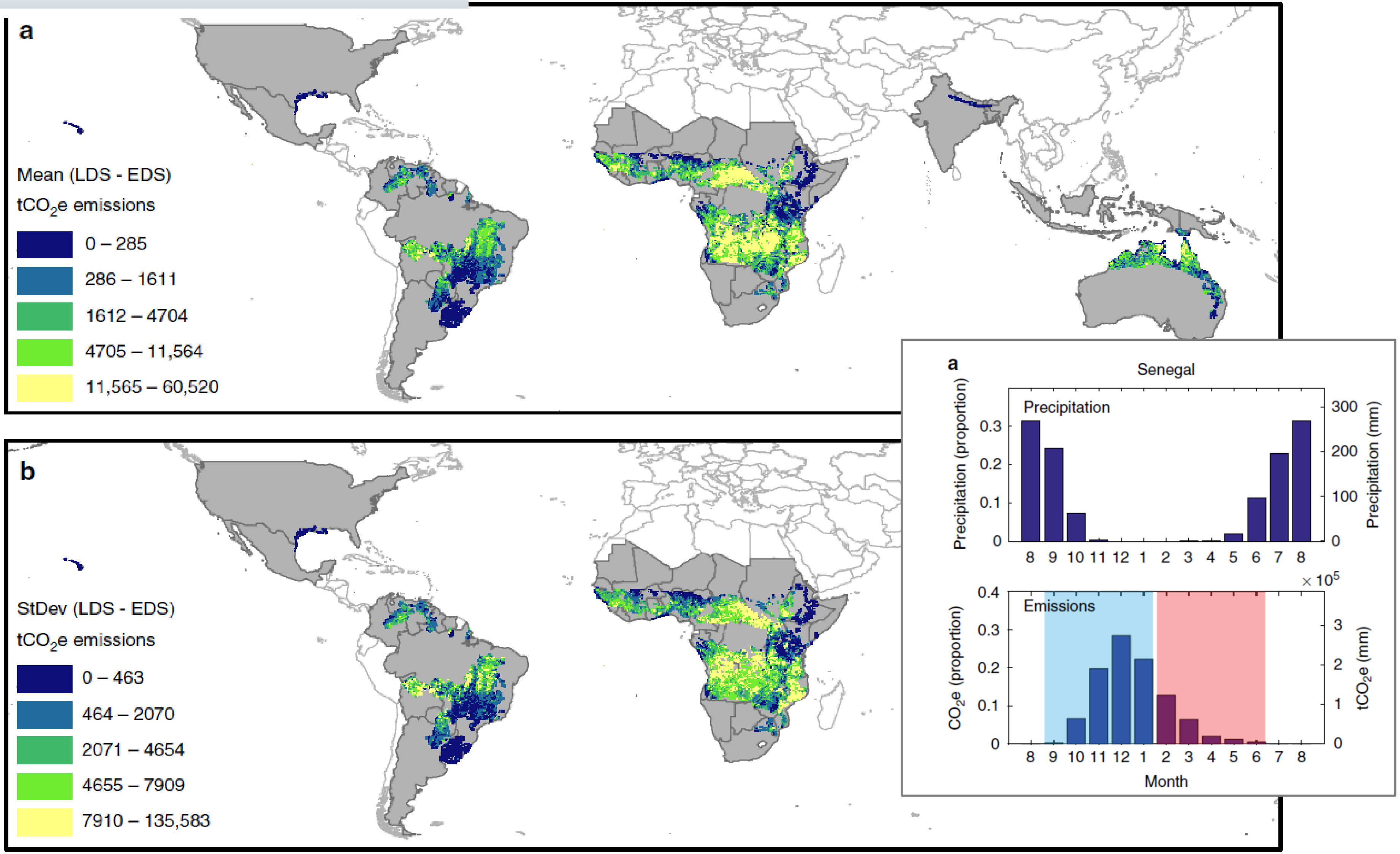


Fig. 1 Mean annual emissions abatement potential and standard deviation. (**a**) Mean annual emissions abatement potential per pixel for the 50 countries (shaded in gray) with savanna habitat with > 600 mm rainfall yr-1, included in this study. Abatement potential is expressed as late dry season-early dry season (LDS-EDS) emissions of the combined N_2O and CH_4 components of savanna burning, represented in tCO_2-e. Data categories are illustrated using quantile symbology. (**b**) Standard deviation of annual emissions abatement potential per pixel

POLICY:

Increase **early** and reduce **late** burning to reduce GHG emissions (Lipsett-Moore et al 2019)

West Africa has high potential, how would this work?

Early burn in Mali

Key parameters for determining methane and other emissions: Burned area (BA), fuel consumption (FC) = (fuel load (FL) * combustion completeness(CC)) and gas specific Emission Factor (EF)

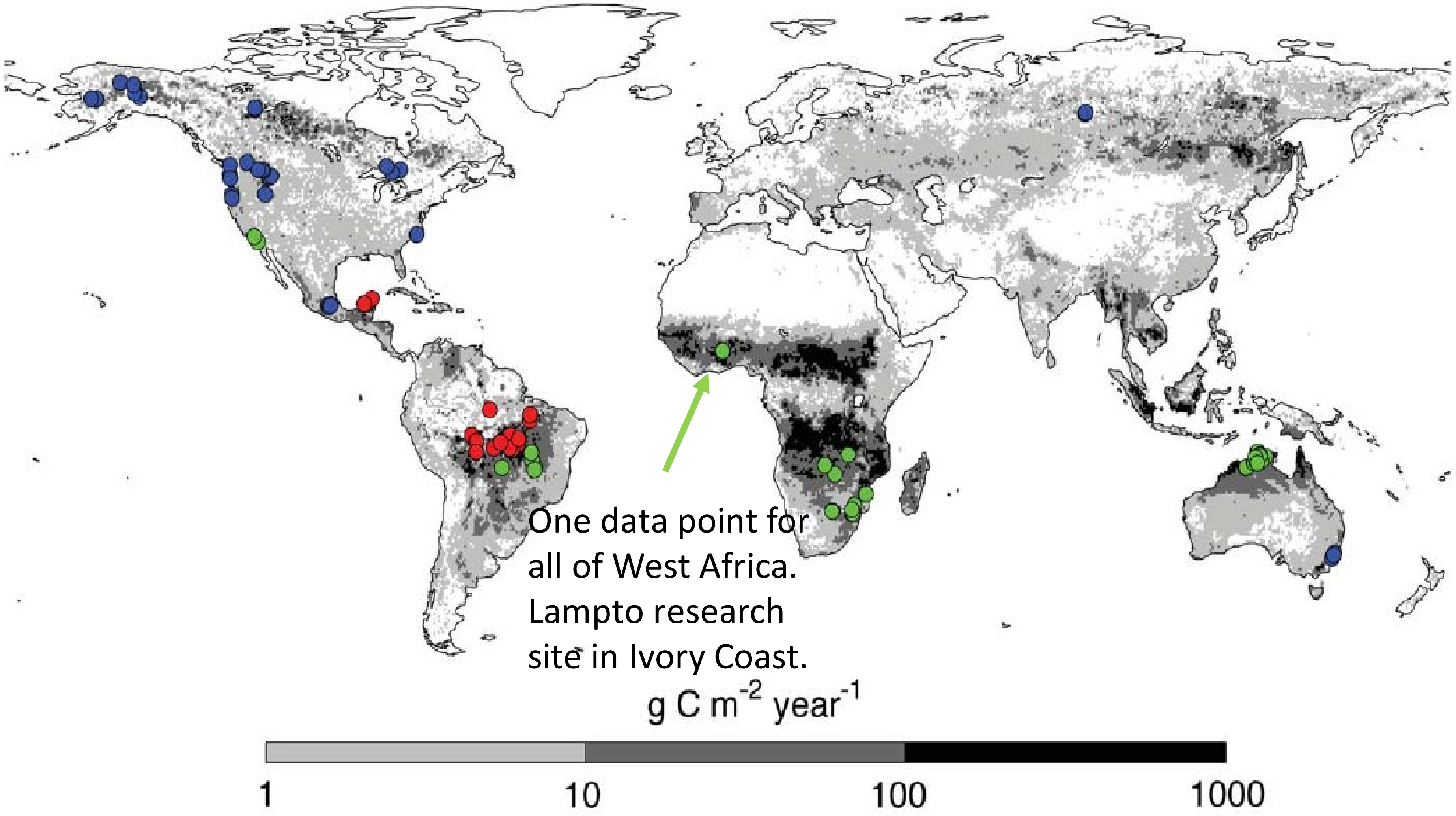
Data Sources:

BA: Satellite image analysis
FL: Field and remotely sensed data
CC: Field study
EF: Field (or airborne) study

Emissions = BA*FL*CC*EF

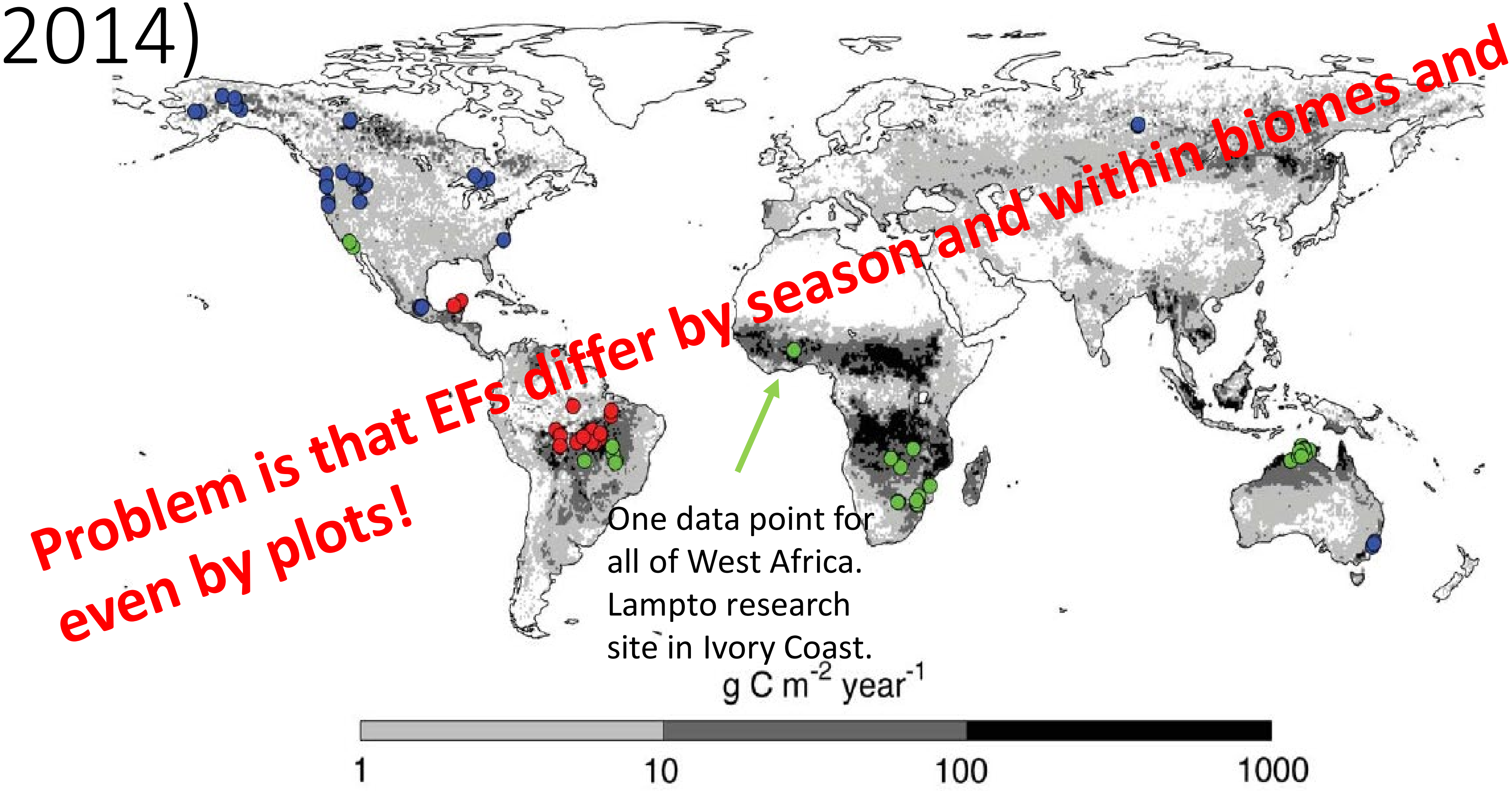
Burned test plot, Mali

Lack of data: Locations where GHG EFs and biomass (FL) were measured (van Leeuwen et al)



One data point for all of West Africa. Lampto research site in Ivory Coast.

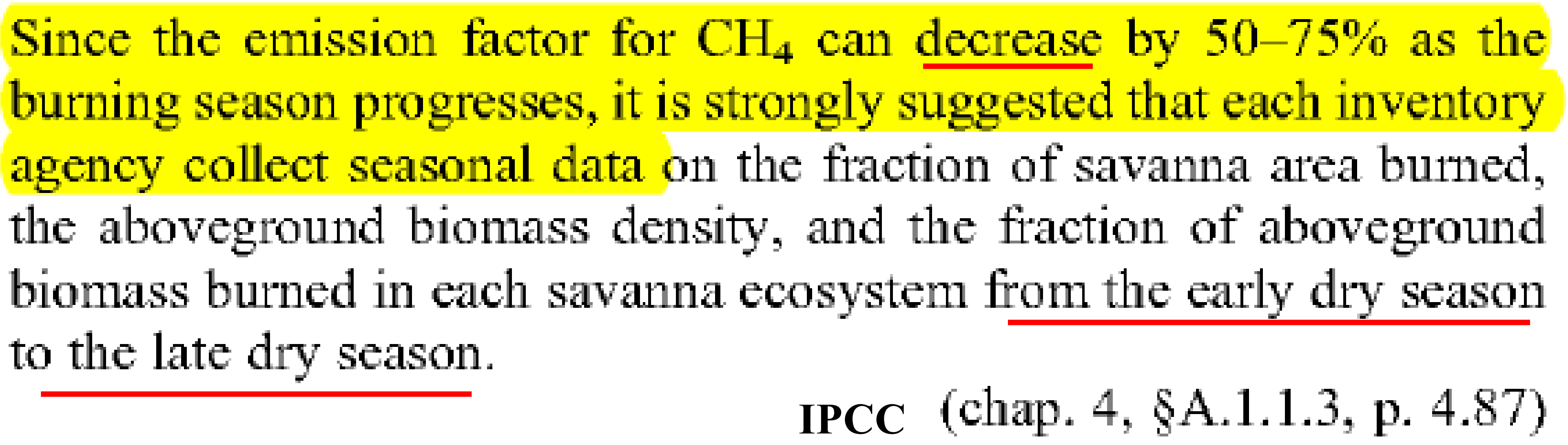
Lack of data: Locations where GHG EFs and biomass (FL) were measured (van Leeuwen et al 2014)



Problem is that EFs differ by season and within biomes and even by plots!

One data point for all of West Africa. Lampto research site in Ivory Coast.

Early/Late: IPCC finds key emission factors ***decrease*** by season; early fires have higher methane EF than later fires



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 (chap. 4, §A.1.1.3, p. 4.87)

Problem is that EFs are based on little data, usually biome average

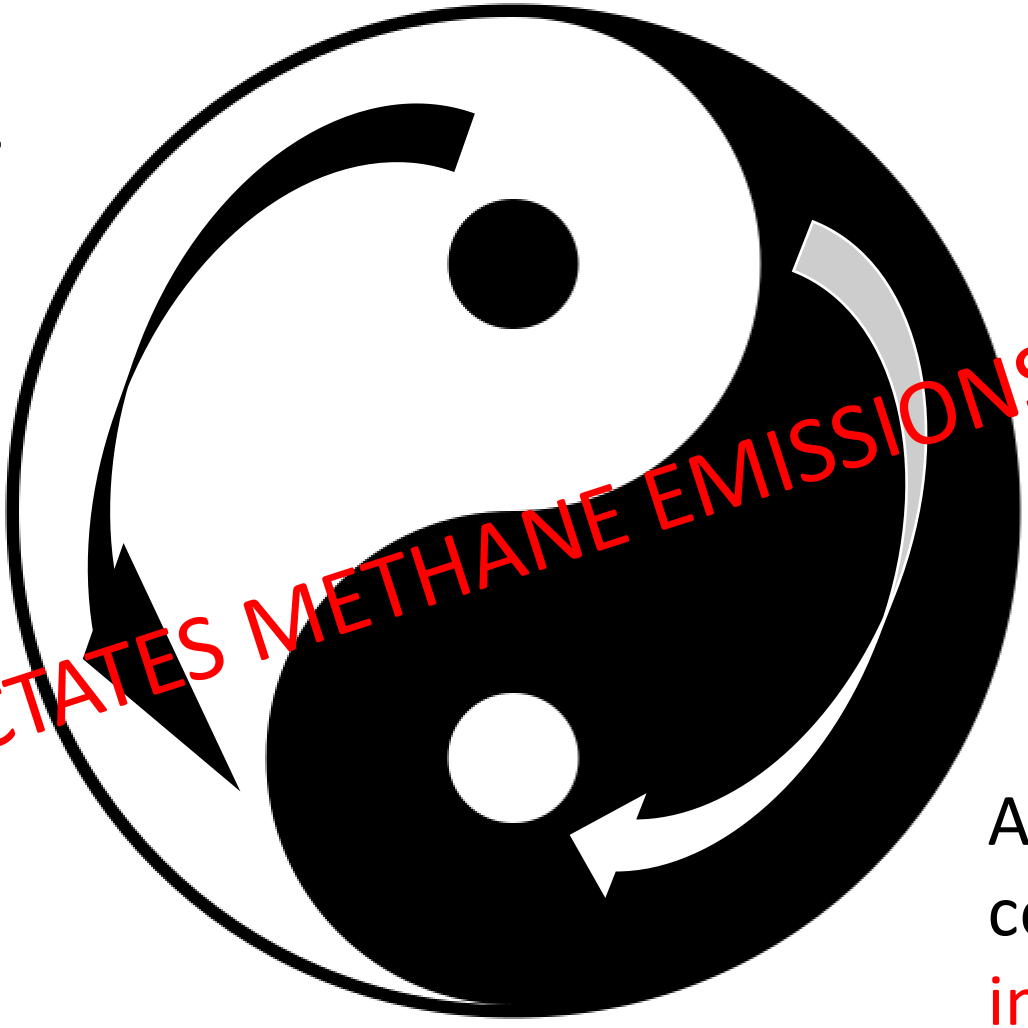
Yin and yang of methane emissions over fire season

CH_4 Emission factor decreases as dry season progresses (Moister fuels burn less completely, release more methane)

Area burned and combustion completeness increases as dry season progresses (fuels dry more uniformly)

Yin and yang of methane emissions over fire season

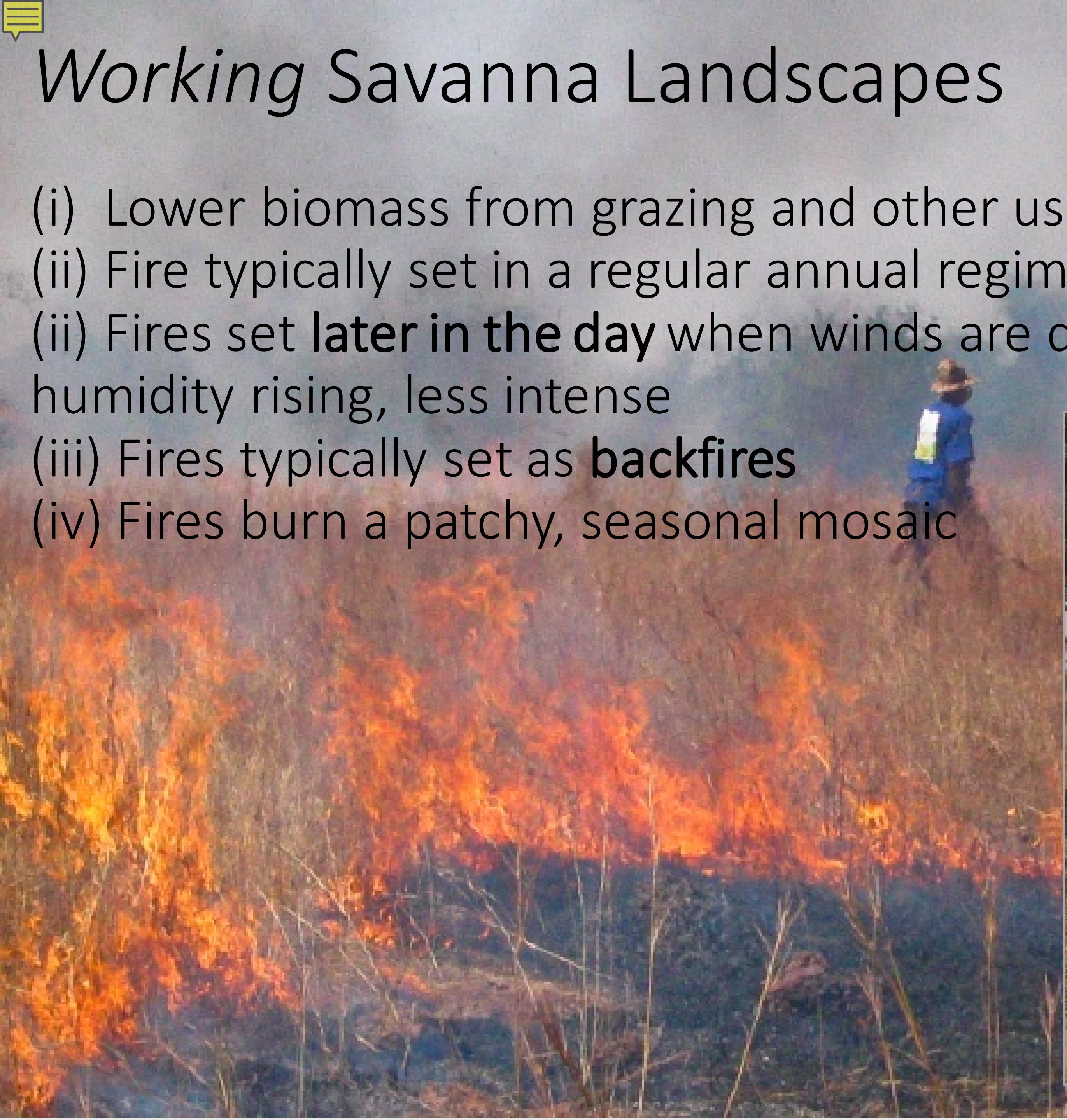
CH_4 Emission Factor decreases as dry season progresses



WHICH FACTOR DICTATES METHANE EMISSIONS IN A SAVANNA?

Area burned and combustion completeness increases as dry season progresses

Working Savanna Landscapes



(i) Lower biomass from grazing and other uses (about ½)
(ii) Fire typically set in a regular annual regime (not random)
(ii) Fires set **later in the day** when winds are dropping and humidity rising, less intense
(iii) Fires typically set as **backfires**
(iv) Fires burn a patchy, seasonal mosaic

Research Question: Can burning “earlier” reduce emissions from West African savanna fires?

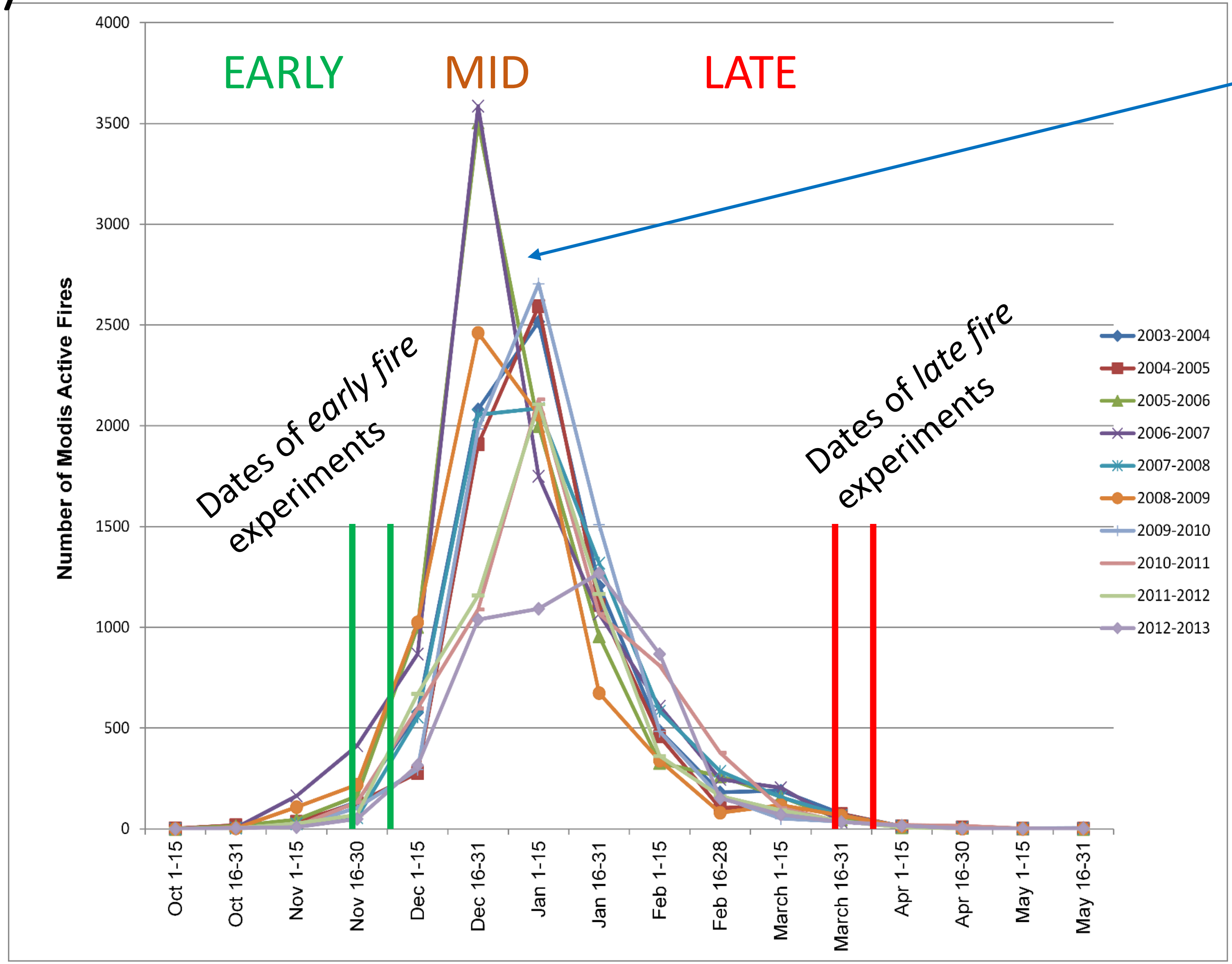
What do we need to know?

1. Burned area by season (actual burning regime)
2. Fuel load by season
3. Combustion completeness
4. Emission factors by season

Focus of this study

Peak burning is in the mid-season, but most **experiments** done early or late*

Fire regime begins early and peaks in late December—what we refer to as mid-season



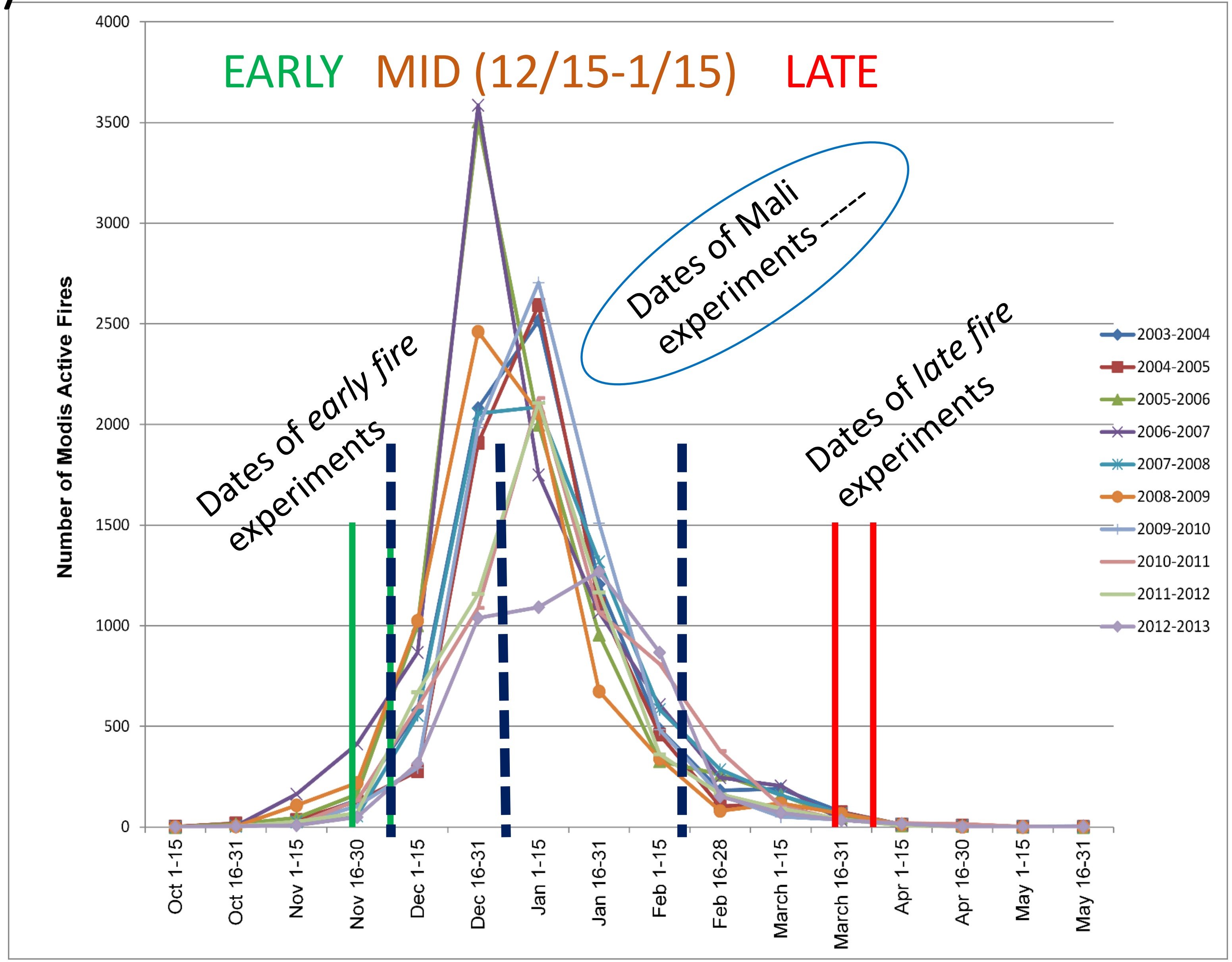
Lack of data from the middle fire season, when *most* fire occur

Laris et al 2017

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

Peak burning is in the mid-season, but most **experiments** done early or late*

Fire regime begins early and peaks in late December—what we refer to as mid-season



AVE landscape % burned

EARLY 50%;

MID 40%;

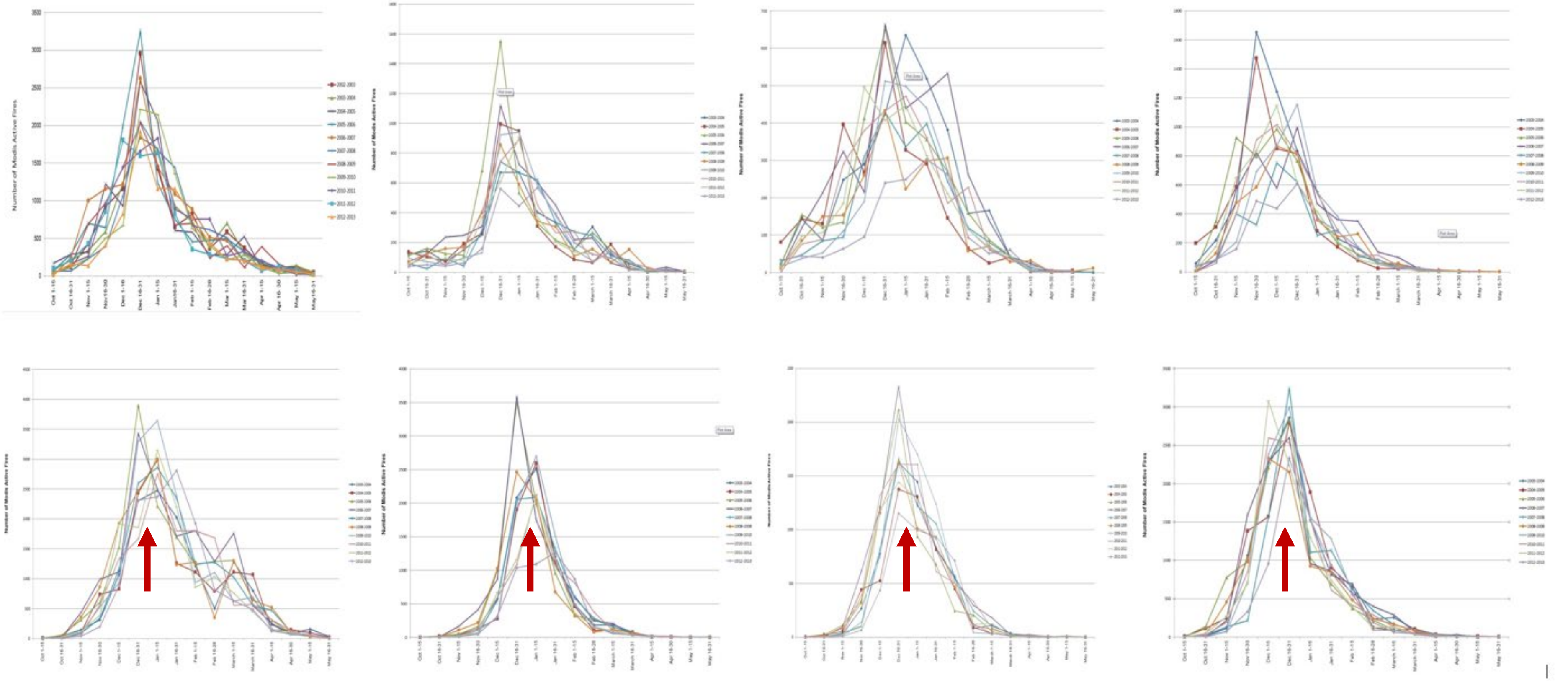
LATE 10%

Early and Mid cover about 90% of fires*

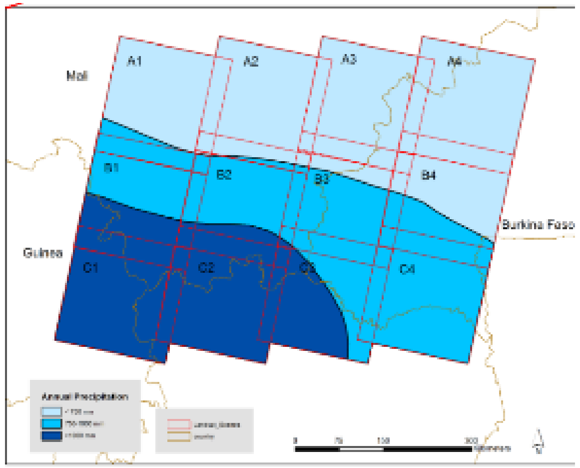
* Based on Landsat data analysis

Laris et al 2017

Regional Phenomenon: Regular annual timing of fire, especially in *mesic* zones of West Africa

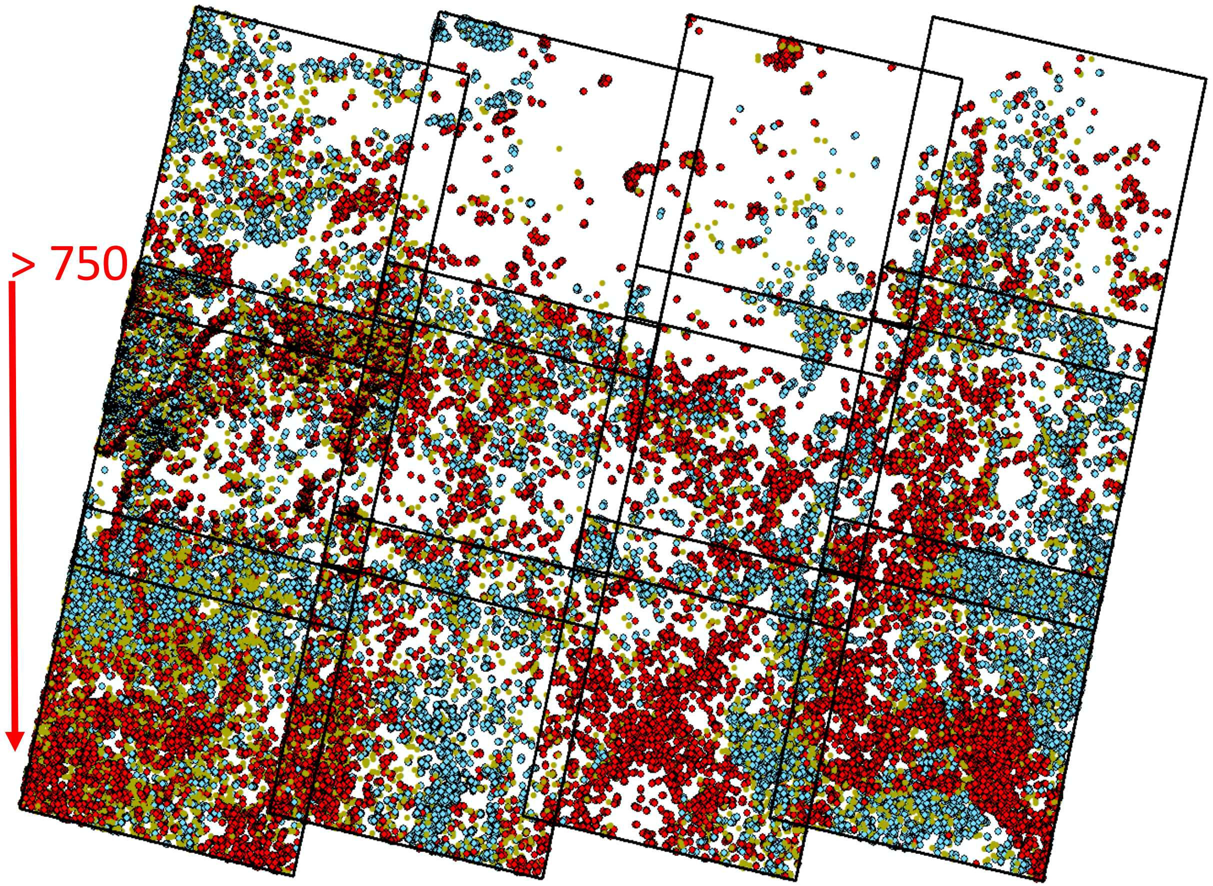


Precip > 750 mm

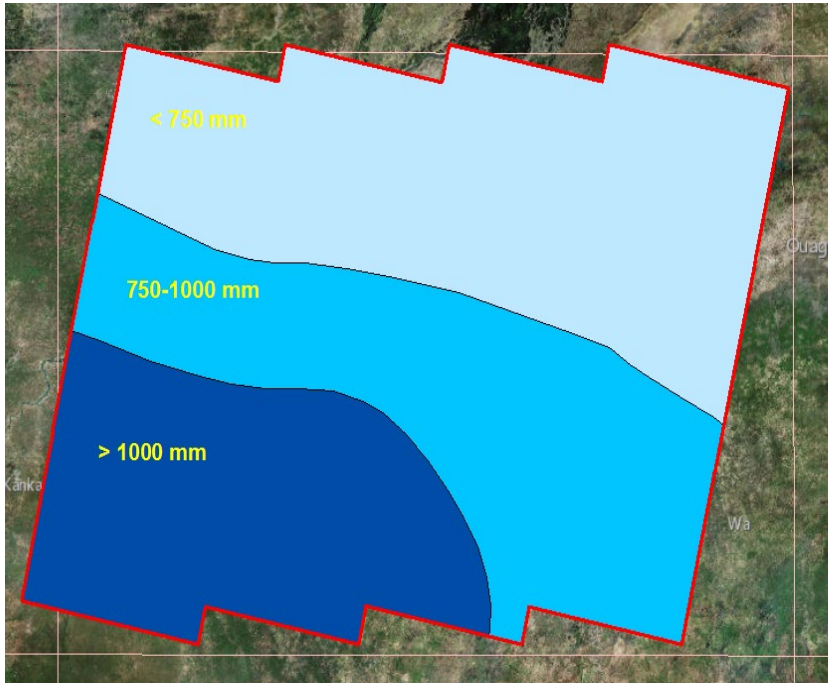


S. Dadashi et al 2015

Regular annual *spatiotemporal pattern* of fire (Precip > 750mm)



Blue areas regularly burn *early*, red areas regularly burn *later*

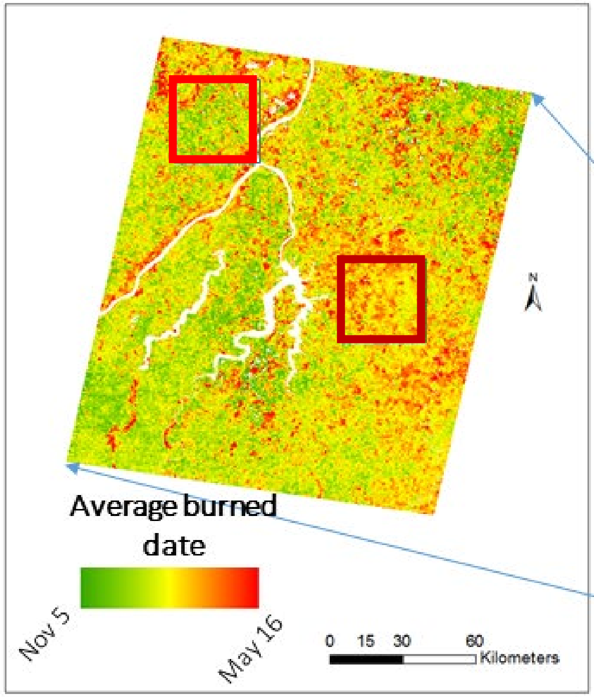


Late-Late 🟥 LL
Early-Early 🟦 EE
No Pattern ●

We use this data to select burn plots and dates

Laris, P., S. Dadashi et al. 2016. ***Plant Ecology***

Study areas in southern Mali: 2 working landscapes

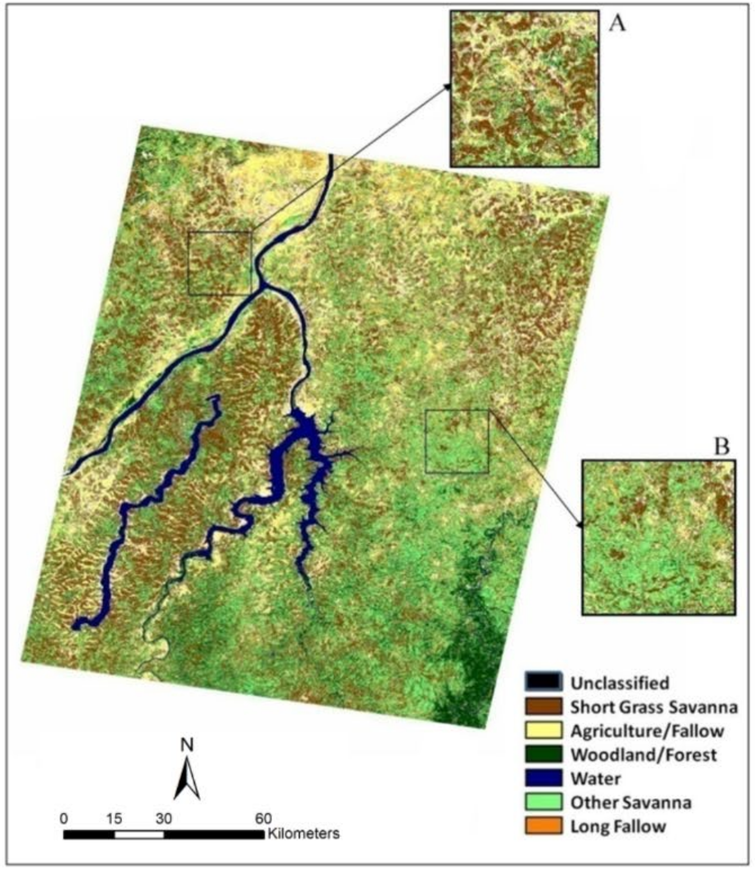


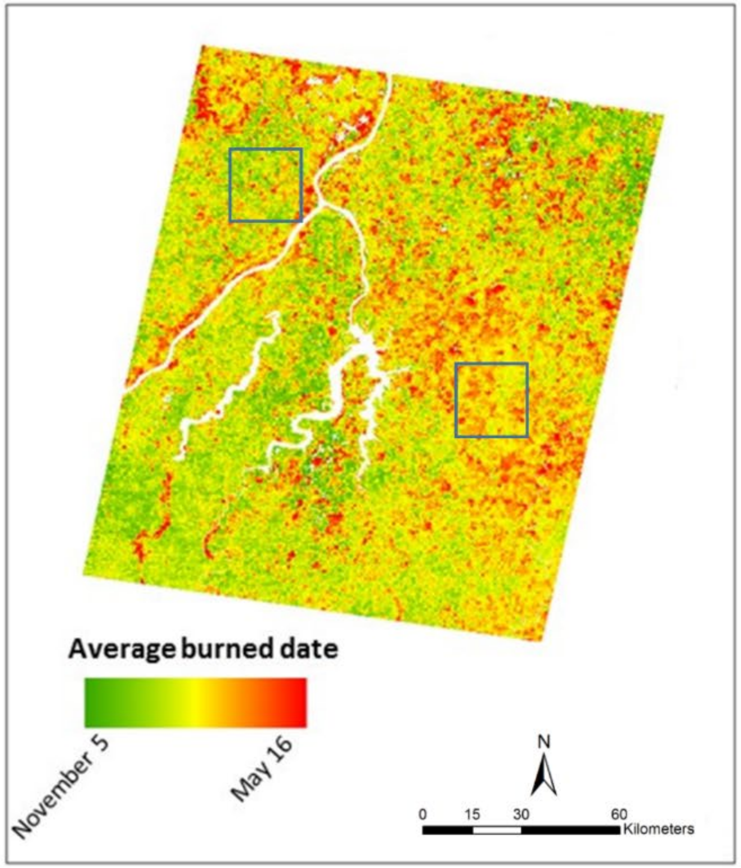
□ Sub areas for interviews and fire experiments

Dry (fire) season from Nov.-May

Vegetation and Fire regime are linked in a seasonal-mosaic burning regime with regular spatiotemporal pattern:

People burn grasses as soon as dry in an annual progression, from short annuals to tall perennials

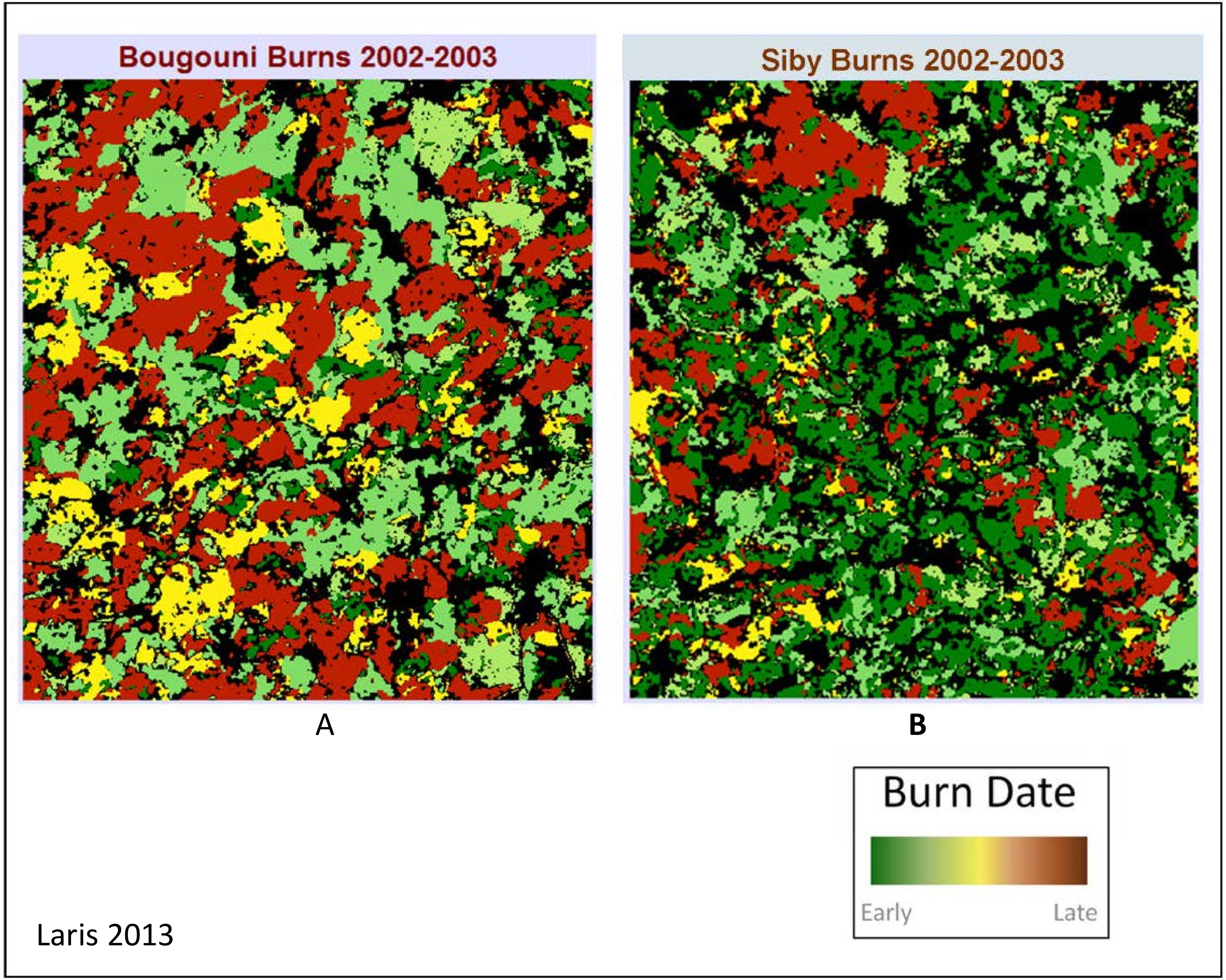




Laris, 2011; Laris, Caillault et al 2015

Two regions with different fire regime

The difference explained by the higher vegetation heterogeneity and greater extent of dry laterite plateaus in area B



Laris 2013

Burned Area from Landsat – 50% of land burns 90% of fires occur in Early - Mid Season

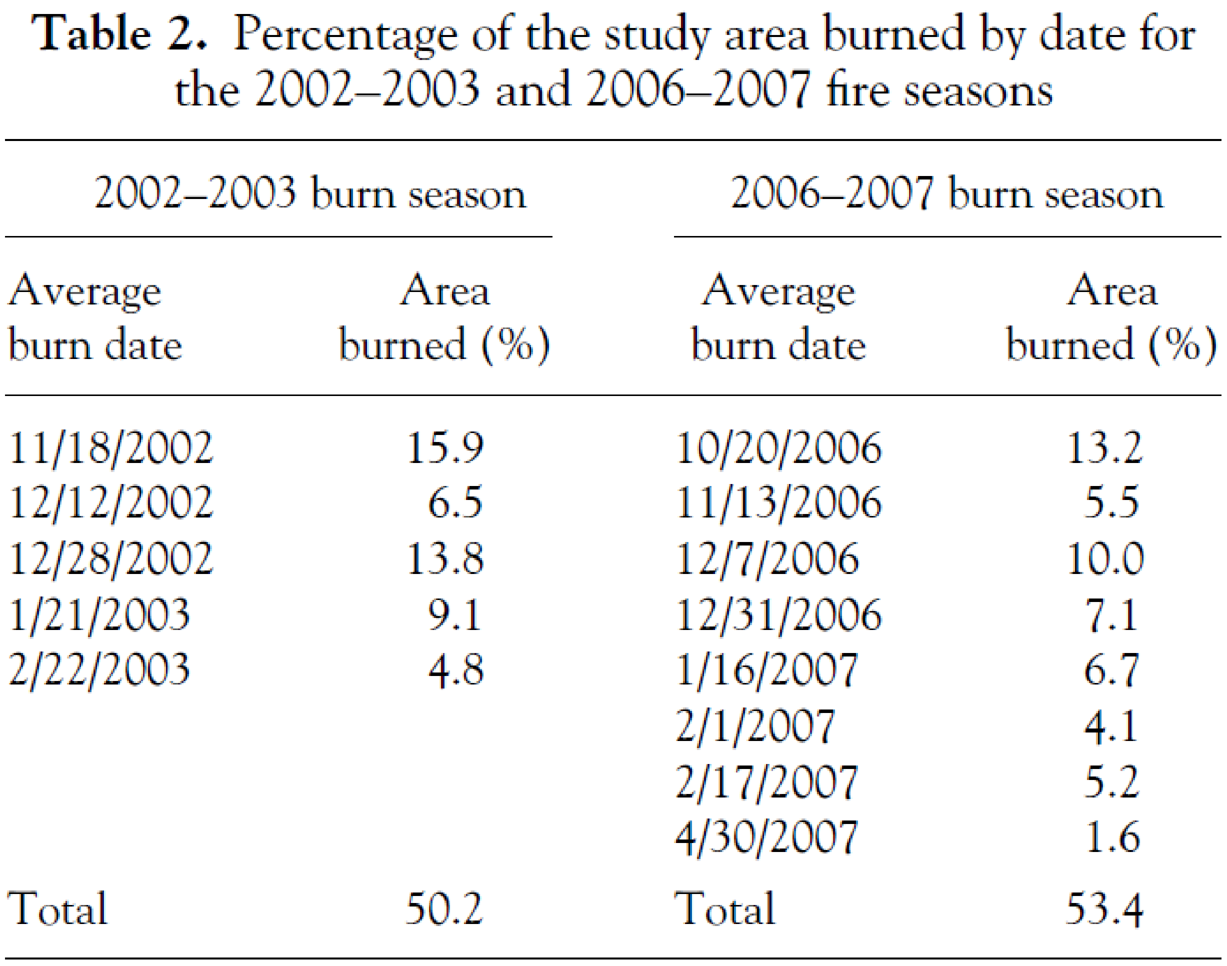
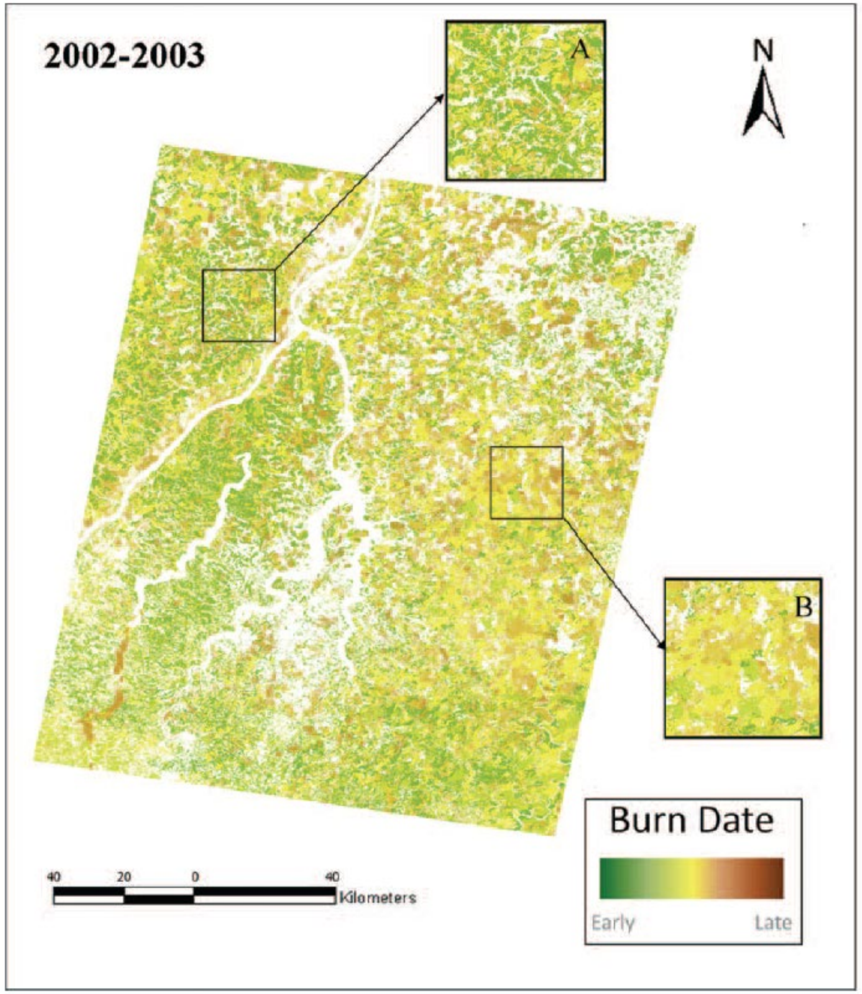


Table 2. Percentage of the study area burned by date for the 2002–2003 and 2006–2007 fire seasons

2002–2003 burn season		2006–2007 burn season	
Average burn date	Area burned (%)	Average burn date	Area burned (%)
11/18/2002	15.9	10/20/2006	13.2
12/12/2002	6.5	11/13/2006	5.5
12/28/2002	13.8	12/7/2006	10.0
1/21/2003	9.1	12/31/2006	7.1
2/22/2003	4.8	1/16/2007	6.7
		2/1/2007	4.1
		2/17/2007	5.2
		4/30/2007	1.6
Total	50.2	Total	53.4



AVE landscape % burned = EARLY 25.6%; MID 20.4%; LATE 5.8%

Source: Laris 2011

Our Study: Replicate anthropogenic fire regime in *working* landscapes of Mali (100+ experimental fires)

Local hunter/fire manager setting an early fire in 2000

- Fire regime (seasonality) set according to local practice and long term patterns
- Biomass (fuel load) based on working lands
- Fires set according to local practice (afternoon, light winds, mostly back-fires)

Two methods to measure emissions:

1. Real time progressive gas analyzer data (n=100)
2. Canister data (lab analysis) (n=40)

Research team in the field in Mali

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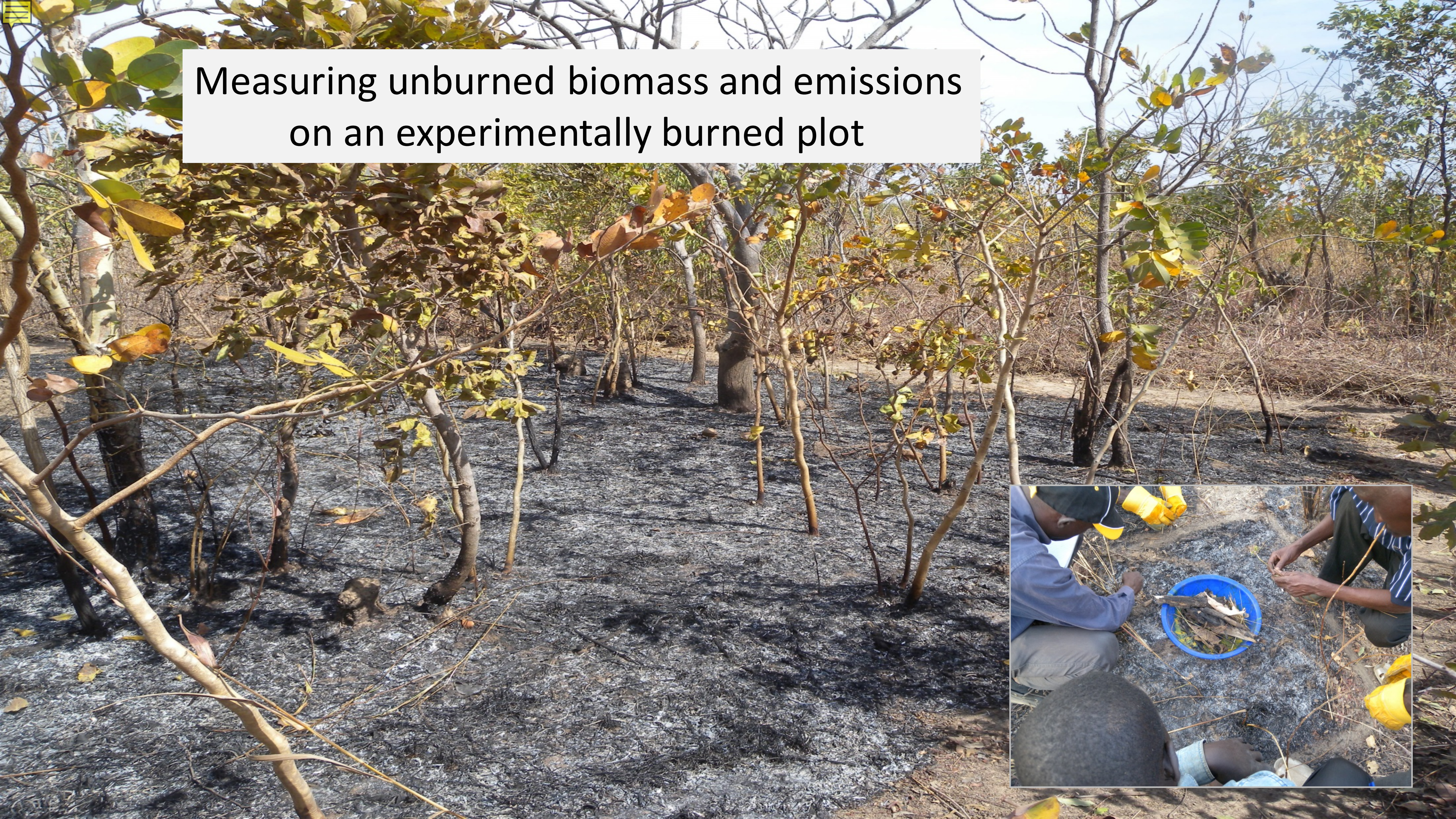
Measuring unburned biomass and emissions on an experimentally burned plot



RESULTS: What do field measurements tell us?

Mean Fire Characteristics by Study Period
Fire experiment plot data (n=100+)

Low-Med-High

Mean plot characteristics	Early	Middle	Late
Dry biomass (tons/hectare)*	**3.83** (1.27)	**3.87** (1.37)	3.71 (1.74)
Grass biomass (percent)	92 (18)	80 (22)	77 (19)
Temperature (Celsius)	32.7 (3.5)	30.5 (3.3)	36.5 (3.0)
Relative humidity (percent)	28.8 (5.3)	28.1 (9.6)	17.3 (4.6)
Wind speed (meters/second)	1.1 (0.55)	1.5 (0.59)	0.90 (0.53)
Spread rate (meters/second)	0.032 (0.02)	0.031 (0.03)	0.034 (0.02)
Scorch height (m)	1.32 (0.53)	1.26 (0.66)	1.73 (0.61)
Visual efficiency (%)	83.3 (12)	93.5 (11)	95.0 (5)

(standard deviations in parentheses)

* Note: about ½ protected biomass values for the region

Canister data shows mid-season drop in CH_4 EF

Canister Data (n=35)	MCE (flame)	EF_CH4 (flame)	MCE (all)	EF_CH4 (all)
Early Fire	0.88	3.75 ↓	0.813	5.96
Mid Fire	0.92	2.85	0.922	2.71
Head fire	0.88	4.31	0.884	4.31
Back fire	0.90	2.96	0.858	4.53
Mid Head	0.90	4.16	0.901	4.18
Mid Back	0.93	2.47	0.892	3.80
Early Head	0.87	4.46	0.866	4.33
Early Back	0.87	3.51	0.770	7.28
TOTAL	**0.90***	**3.30***	0.863	3.64

Biome averages from Andreae 2019 are: MCE= 0.94 (± 0.02) and **EF CH4 = 2.7 (± 2.2)**

Thus early fires have higher methane EF that biome average and mid-fires by 30%

RESULTS: Fire-line intensity values vary by *fire type*

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

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

Type of fire	n=83	Mean	Minimum	Maximum
Head	40	336.26	48.52	1395.36
Back	43	124.24	24.69	476.94

- Intensity values are **significantly lower** than other studies given fire timing (low winds) and **lower biomass of working landscapes**.
- High variation in results as expected.

Canister data shows higher CH_4 EF for head fires

Canister Data (n=35)	**MCE (flame)**	**EF_CH4 (flame)**	**MCE (all)**	**EF_CH4 (all)**
Early Fire	0.88	3.56	0.813	5.96
Mid Fire	0.92	2.71	0.922	2.71
Head fire	0.88	**4.31** ↑	0.884	4.31
Back fire	0.90	**2.96**	0.858	4.53
Mid Head	0.90	4.16	0.901	4.18
Mid Back	0.93	2.47	0.892	3.80
Early Head	0.87	4.46	0.866	4.33
Early Back	0.87	3.51	0.770	7.28
TOTAL	**0.90**	**3.14**	0.863	3.64

Head fires have significantly higher methane EF that biome average for all seasons

Head and Back fires differ for all key factors:

Intensity, Combustion %, Speed & Methane EF

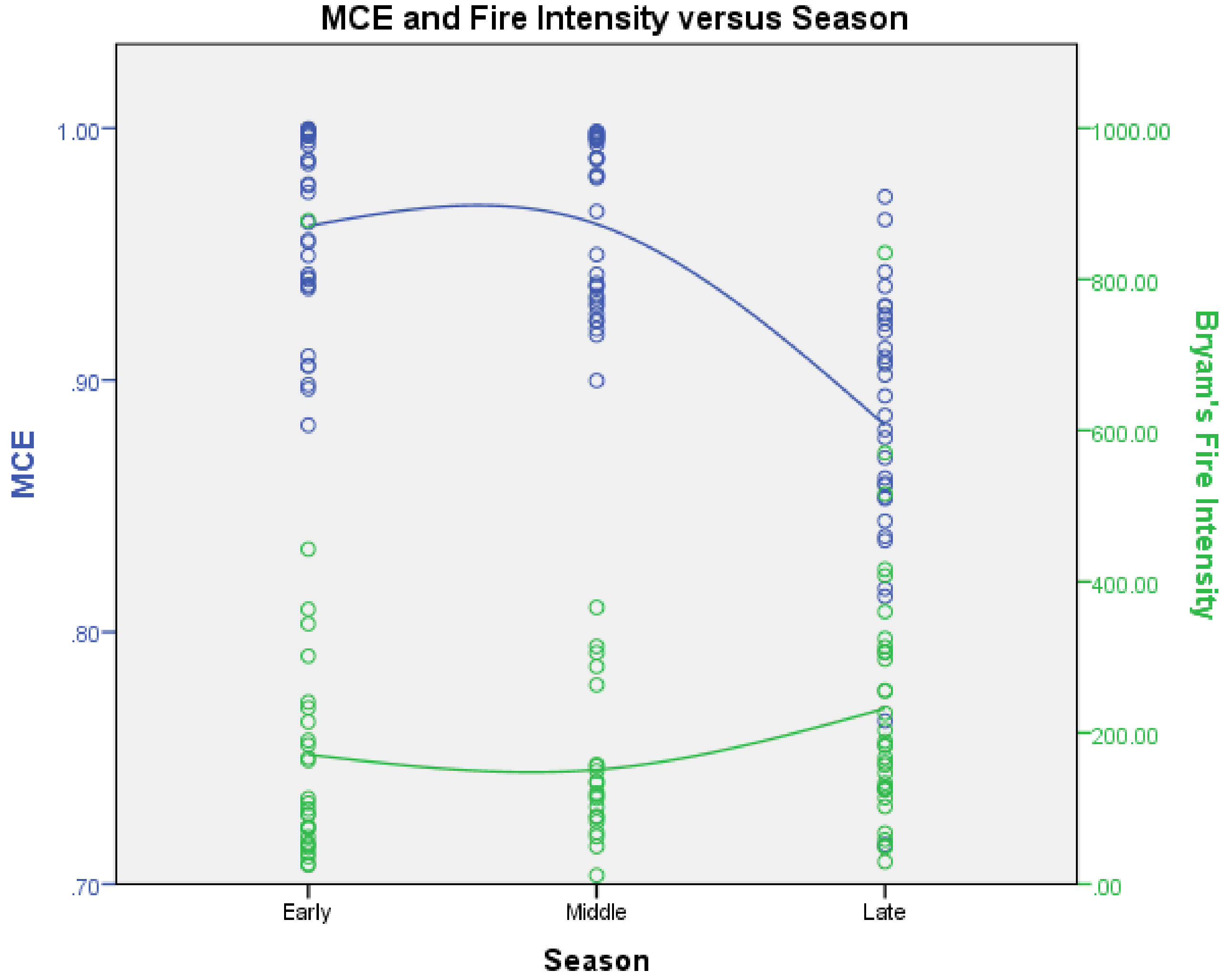
Note: we have **no quantitative data** on % of area burned by fire type

Canister Data (n=35)	**Fire Intensity Kw/m**	**Biomass tons/ht**	**Combustion Completeness %**	**Fire Speed m/s**	**MCE f**	**EF_CH4 f**
Early Season	220.3	3.64	0.873	0.030	0.88	3.56
Middle Season	178.9	3.61	0.887	0.030	0.92	2.71
Head Fires	308.0	3.65	0.855	0.044	0.88	4.31
Back Fires	176.0	3.63	0.890	0.028	0.90	2.96
All Fires (f)	194.4	3.62	0.882	0.030	0.90	3.14

Head fires **burn faster**, with **higher intensity**, lower combustion completeness and **higher Methane** EF
Mid-Season fires **have higher combustion completeness: 0.89 vs 0.87** for early fires

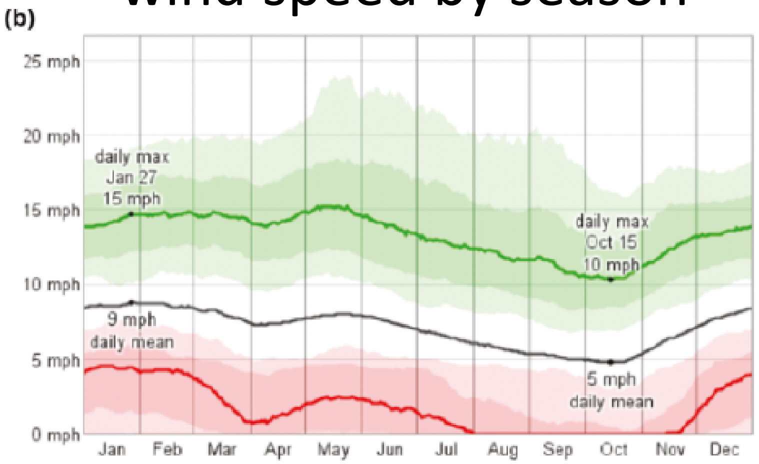
Combustion Completeness increases from Early to Middle to Late season, while fire-line intensity dips in mid-season

N=100	Combustion Completeness	Fire Intensity (kW/m)
All Fires	0.860	230.4
Early Fires	0.820	242.4
Middle Fires	0.850	200.1
Late Fires	0.884	243.8
Head Fires	0.850	357.0
Back Fires	0.860	126.7
Local Practice	0.820	247.7
Random	0.860	220.2

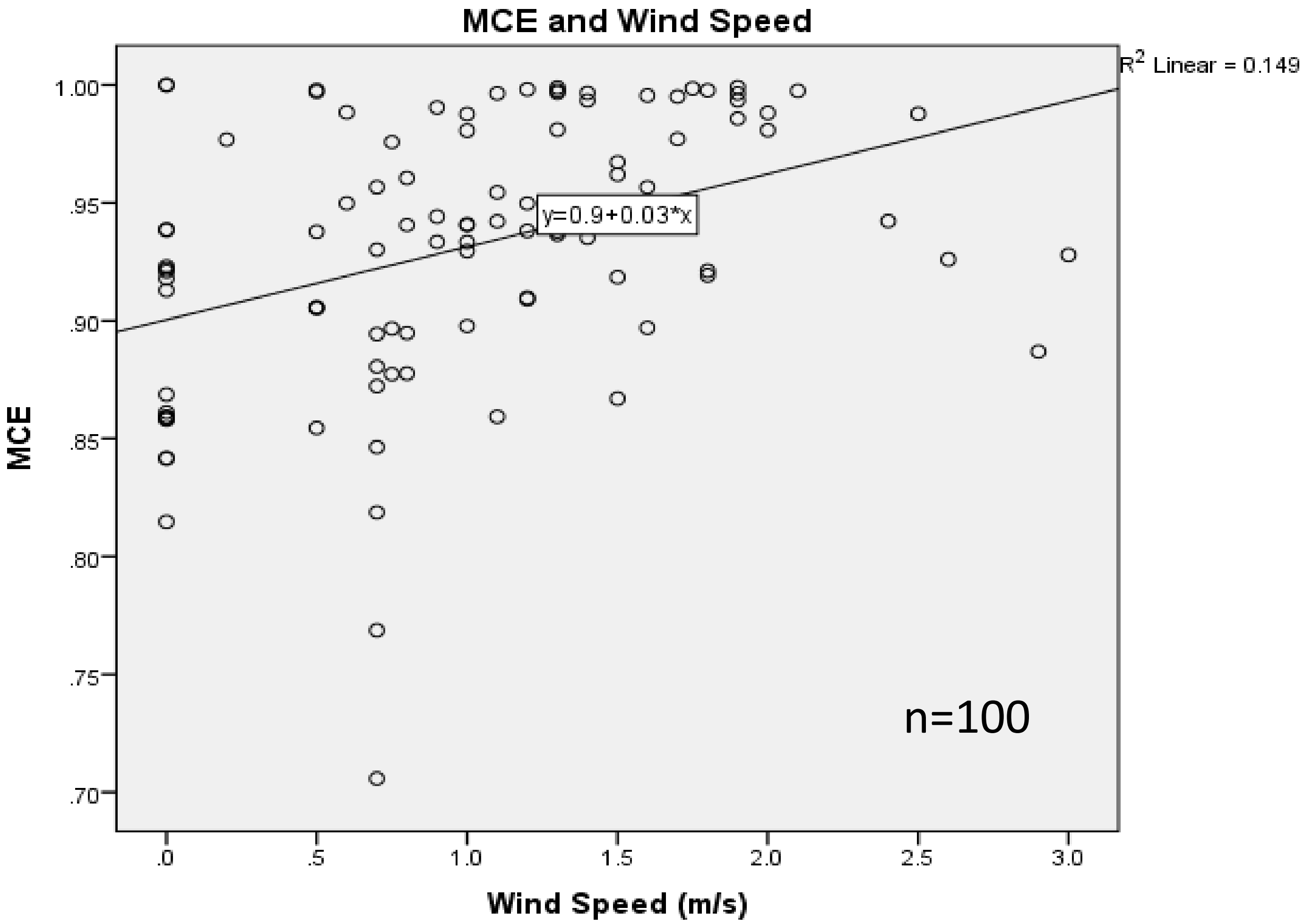


MCE is driven by wind speed which also peaks in mid-season (IMR data)

wind speed by season



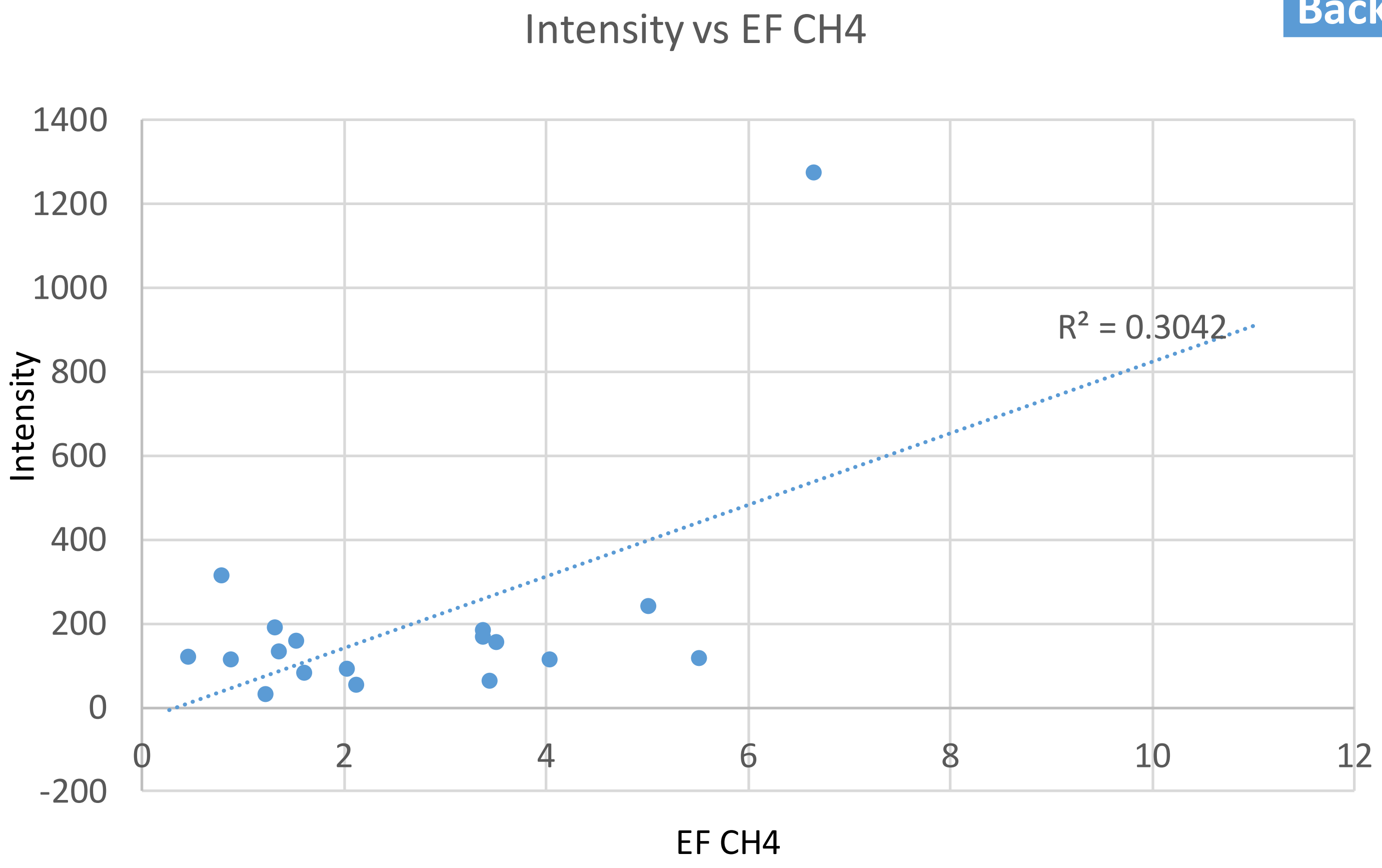
Note that wind speeds are generally quite low and thus lower fire speed and fire-line intensity than other savanna studies



n=100

Methane increases with fire intensity and is a function of fire type

Canister Data (f)	MCE	EF_CH4
Head fire	0.88	4.31
Back fire	0.90	2.96



Historic BA Data indicates a shift to later (mid) fires in southern Mali study area of Bougouni (15 days)

Average Burn Dates and Standard Deviation by land cover type for the contemporary and historic burn periods based on Landsat imagery (1 = 1 November).
Note: significant agricultural increase in area during this period

	Contemporary (1999–2007)		**Historic (1972–1991)**	
	Bougouni	**Siby**	**Bougouni**	**Siby**
Short Grass Savanna	44.5 (26.1)	29.2 (22.5)	36.0 (18.2)	36.6 (21.9)
Agriculture/Short Fallow	49.2 (31.3)	44.3 (32.7)	37.6 (19.4)	44.3 (29.0)
Savanna/Long Fallow	61.5 (29.4)	59.7 (34.5)	44.2 (21.4)	52.0 (30.7)
Forest/Woodland	72.9 (35.6)	76.2 (36.6)	48.3 (24.0)	60.0 (33.0)
All cover types	**57.7 (30.5)** Mid-Season	**48.1 (34.3)**	**42.8 (21.3)** Early Season	**47.0 (29.3)**

Leaf litter increases over time during the dry season and is highest in late season influencing fire characteristics; specifically MCE drops

Leaf litter on plot in late January

Observation indicates that methane spikes when burning green leaves on small trees; higher intensity means taller flames and more leaves combusted.

What to conclude?

- Combustion completeness increases from 82% to 85% to 88% from early to mid to late (3-6% increase)
- Methane emission factor decreases from Early to Mid by 30%
- People already burn majority of landscape early (as soon as grasses are dry). If pushed earlier EF Methane might increase further.
- Doubtful than any reduction in area burned by early fires can offset 30% increase in EF
- Back fires have lower Intensity and CH_4EF for all seasons
- Leaf litter increases in mid to late season, with impact on MCE (methane?)

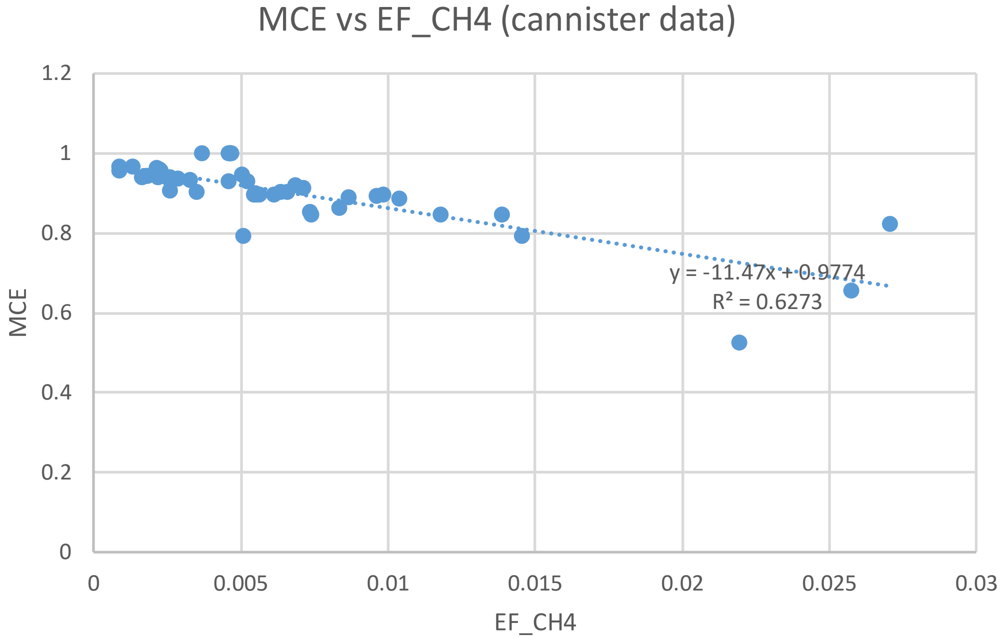
What to conclude about *working* lands fires?

- People set back fires which have lower intensity and lower methane EFs than head fires
- Biomass is lower by about ½ on working lands, resulting in lower intensity fires
- Afternoon fires have lower winds, higher humidity and thus, lower intensity.
- Lower intensity fires are less damaging to small trees ***and*** release less methane
- **Anthropogenic fire regime currently "positive" for GHG emissions, policy not warranted—indeed policy may *increase* methane*!***

Closing Question: Do CO and CH_4 always correlate? Do fuel *moisture* driven low MCE and fuel *structure* driven low MCE fires have the same CH_4/CO ratio?

Fuel moisture driven

Fuel structure driven



Ward (1996) found that the grass/leaf ratio was a critical determinant of emission factors. MCE as low as 0.85 for sites with ample litter compared with an upper limit of 0.96 for those with grassy fuels

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

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