Module 2.6 Estimation of GHG emissions from biomass burning

Module developer:

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After the course the participants should be able to:

- Understand the strengths and limitation of satellite remote sensing of fire
- Describe a range of fire monitoring approaches and techniques
- Use available fire products to calculate emissions from biomass burning

V1, May 2015

Background material

- GOFC-GOLD. 2014. *Sourcebook*. Section 2.6.
- IPCC. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, vol. 4, ch. 2, "Generic Methodologies Applicable to Multiple Land-use Categories)," with particular regard to section 2.4.
- GFOI. 2014. *MGD* (*Integrating Remote-sensing and Ground-based Observations for Estimation of Emissions and Removals of Greenhouse Gases in Forests: Methods and Guidance from the Global Forest Observation Initiative*).
- GOFC-Fire Implementation Team Portal. http://gofc-fire.umd.edu/

Outline of lecture

1. Fire in the global environment
2. Biomass burning monitoring for REDD+
3. IPCC guidelines for estimating fire-related emissions (CO_2 and non-CO_2)
4. Fire monitoring from satellites:
    - Detection of active fires
    - Mapping of postfire burned areas
5. Available remote sensing fire products (Global burnt areas JRC, MODIS active fires and burned areas, FIRMS, etc.)
6. Calculating GHG emissions from biomass burning
7. Error sources
8. Other potential uses of fire data for REDD+ support

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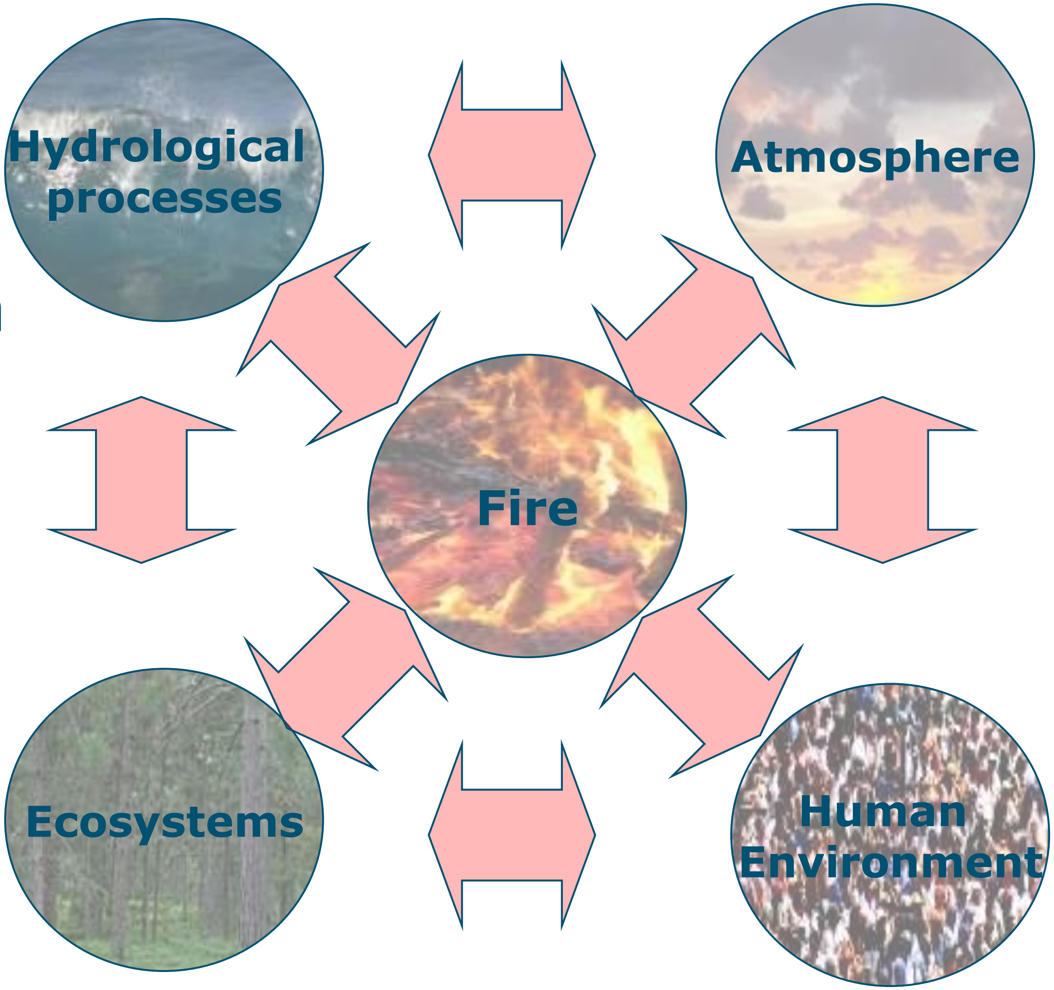
Fire is a global phenomenon: Ten years of fire detections

Why is fire important?

- Fire is:
- A global phenomenon (biomass burning)
- An important and poorly understood Earth system process
- A system of multiple loops and feedbacks



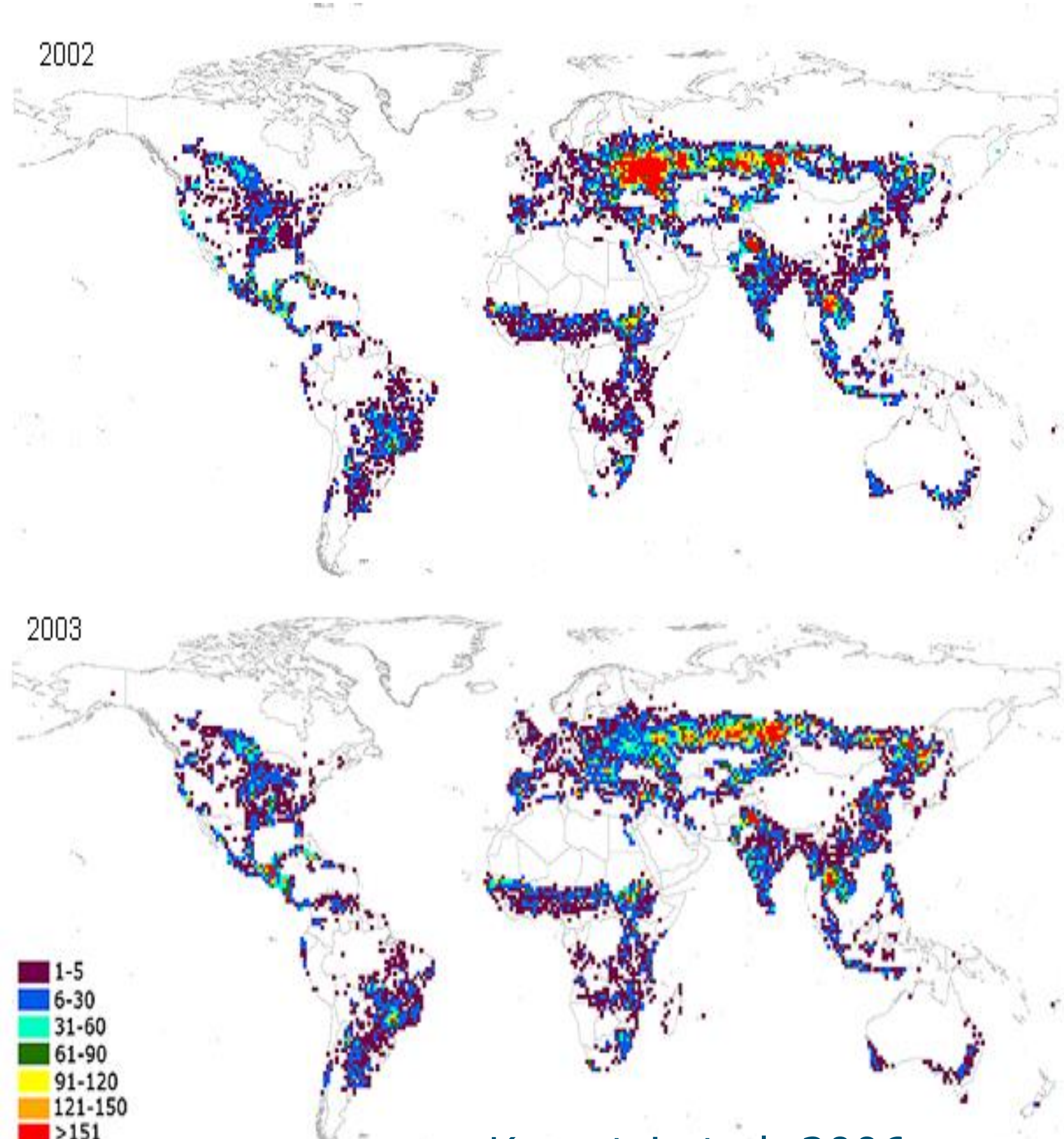
Different fires with different causes

- Natural fires
  - Lightning
  - Volcanoes
- Human-induced fires (>90%, increasing in the past 100 years)
  - Deforestation
  - Important land management tool in tropical and temperate ecosystems
  - Disposing of agricultural wastes
  - Pest control
  - Fuel wood for heating and cooking
  - Production and use of charcoal
  - Arson
  - Cultural ritual

Wildfires and prescribed fires

Agricultural fires

Annual burning of crop Residues a common practice globally



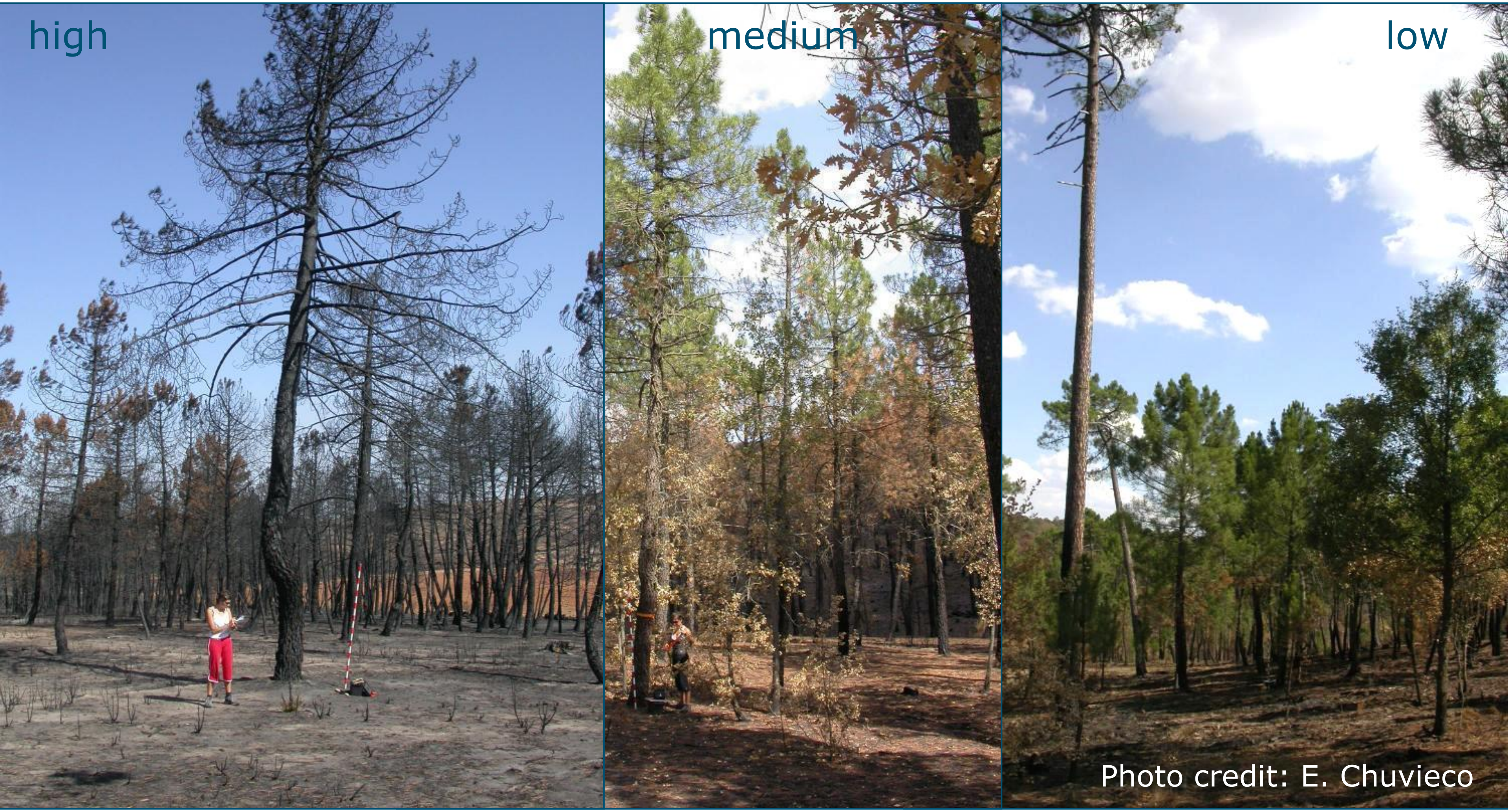
Korontzi et al. 2006.

Impacts of fire:
Wildlife and habitat biodiversity

- Fires have direct mortality on animals.
- Fires may promote and maintain biodiversity.
- Changing fire regimes may pose a threat to biodiversity conservation.
- In several ecosystems, wildfires and invasive species are closely linked.

Charred sheep from the 2007 fires in Greece

Impacts of fire: Forest loss and degradation

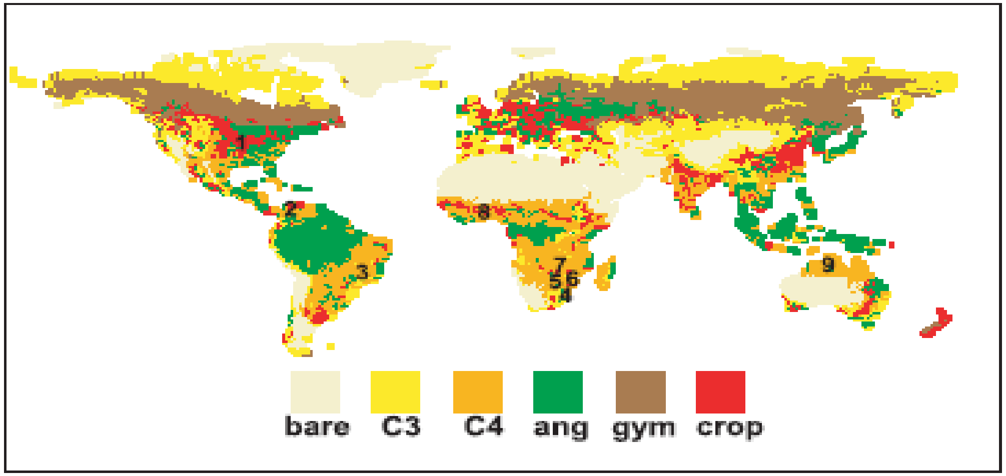


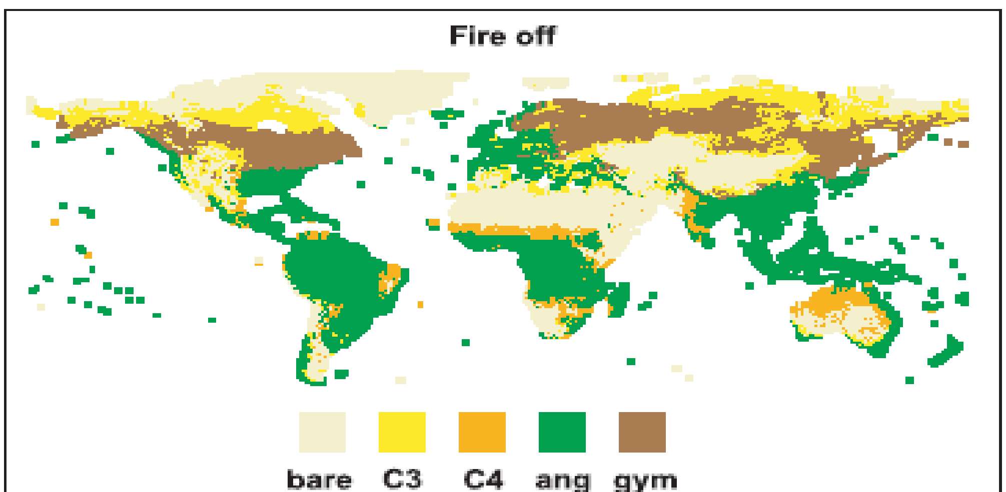
Variations of burn severity

Impacts of Fire: Soils

- Water runoff and soil erosion
- Loss of soil organic carbon
- Need for rapid post fire assessment and treatment

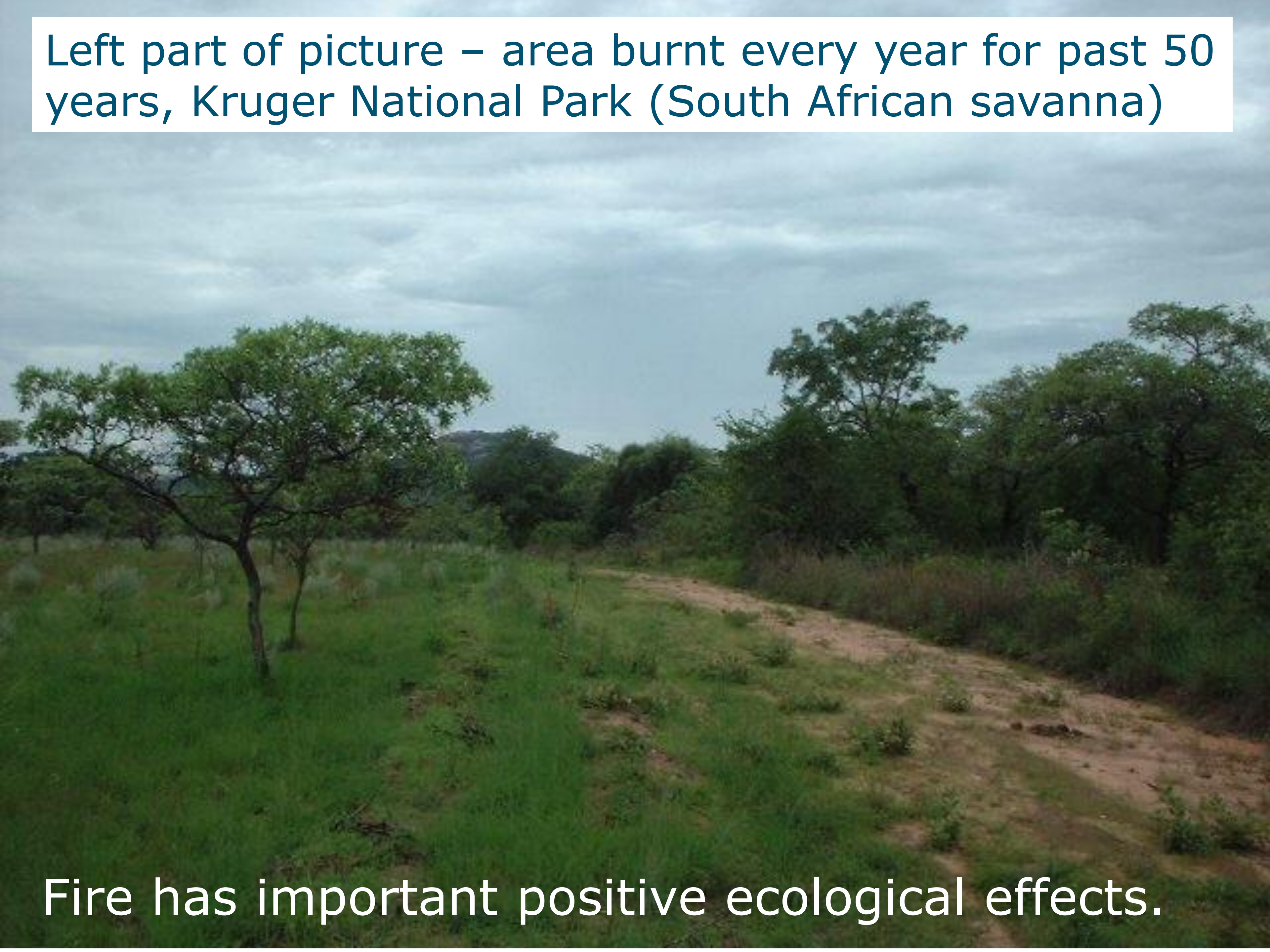
The global distribution of ecosystems in a world without fire





Source: W. J. Bond, *et al*. 2005

Without fire, closed forests would double from 27% to 56% of vegetated grid cells, at the expense of C4 plants but also of C3 shrubs and grasses in cooler climates.


Left part of picture – area burnt every year for past 50 years, Kruger National Park (South African savanna)
Fire has important positive ecological effects.

Plot beside previous slide, unburned for 50 years: same soils, same climate

(William Bond, UCT)

A few global numbers: Why fire matters for REDD+ MRV

- Average global burned area: 3.7 million Km^2 / year (Giglio et al. 2010)
- Fire emissions: not only CO_2, but also significant amounts of trace gases with high greenhouse potential (CO, CH_S, N_2O, NOx), particulate and aerosols
- Average emissions: 2.1 Pg C / year (van der Werf et al. 2010)
- Fires from most biomes contribute to the global fire emissions: savannas (44%), tropical deforestation and degradation (20%), woodland (16%), forest fires (15%), agricultural waste (3%), peatlands (3%) (van der Werf et al. 2010)

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Approaches to monitor fire for REDD+

Approach	Information	REDD+ objective	Suitability
Pre-fire	Early warning system	Protect forest areas at risk and address leakage and permanence	Most suitable for countries with significant amount of wildland fires and known fire regimes
Active fire	Hot spot satellite data	Fire relief and active emissions reduction Support of in-situ actions	Most suitable for countries with large number of small-scale deforestation fires
Post-fire	Burned area estimates	Support estimation of areas of deforestation and degradation	All countries with forest loss due to fire

Fire: A complex biophysical process

- Fire can be seen as:
  - Ecological change agent
  - A disturbance
  - Process associated with land-cover conversion
  - A management tool

- For now, the *Sourcebook* (GOFC-GOLD 2014) covers only emissions from aboveground biomass. More research is needed for monitoring emissions from belowground biomass using standard products and approaches.

REDD+ potential activities related to the agriculture, forestry, and other land use (AFOLU) sector

REDD+ potential activities		**= Forest sector (AFOLU / IPCC)**
Deforestation		= Forest land converted to other land
Degradation	}	
SMF	}	= Forest land remaining forest land
Conservation	}	
Enhancement F C S	}	
Enhancement F C S		= Other land converted to forest land

REDD+ potential activities related to AFOLU sector and fire monitoring

REDD+ potential activities		**Forest sector (AFOLU / IPCC)**
Deforestation	=	Forest land converted to other land
Degradation SMF Conservation Enhancement F C S	=	Forest land remaining forest land
Enhancement F C S	=	Other land converted to forest land

REDD+ activities where fire monitoring can be relevant

Fire activities relevant to REDD+

What fire activities can be relevant to REDD+ in developing countries and require fire emission estimates?

- Mapping and monitoring fire as a disturbance for carbon accounting (forest loss and forest degradation)
- Fire management in fire-prone ecosystems

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IPCC guidelines

- The generic methodology is described in the IPCC (2006) guidelines for national greenhouse gas inventories, vol. 4, sect. 2.4.
- The methodology uses a “bottom up” approach.
- The approach, based on the work by Seiler and Crutzen (1980), is very suitable for implementation in a GIS environment.
- Alternative approaches exist (more on this later), but they are still experimental, and are not readily implementable with off-the-shelf datasets.

IPCC emissions estimation

Bottom up IPCC approach:

$$Lfire = A \times Mb \times Cf \times Gef$$

L = emission for each gas

A = area burned

Mb = fuel load

Cf = combustion factor

Gef = amount of gas released per unit of biomass consumed by the fire

Forest definition

The Marrakech Accords mandate that natural ecosystems with > 30% tree cover are always considered forest and that countries can decide to consider as forest the ecosystems with 10% to 30% tree cover.

- This would include most of the fire-prone savannah ecosystems.
- Emission reduction through fire management could be part of REDD+ actions.

IPCC emissions estimation

- If fire is a disturbance in forest ecosystems, computation is needed of the emissions from deforestation and forest degradation (CO_2 and other gases).

- In savannah and grassland, the IPCC guidelines assume that there is full regrowth within the year, so CO_2 emissions are balanced by carbon absorption (but CH_4 and N_2O are not!).

Data needs for emission estimation

For a bottom-up emission estimation, one needs the following, spatially and temporally distributed:

- Burned areas (*available, with caveats*)
- Biomass (*available, with caveats*—models and land-cover maps)
- Combustion completeness (very uncertain)
- Emission factors (*available, with caveats*—temporal variation not well characterized)

Available data for emissions estimation

- Existing global products have sufficient detail for a Tier 1 fire emission calculation.

- Tier 2 and tier 3 assessments are possible but cannot rely solely on available global products!

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Satellite products

Active fires versus burned areas

A fundamental distinction!

Satellite products

- Active fires = fires actively burning at the overpass time of the satellite (example: MODIS MOD14 product), detection mostly based on mid-infrared (MIR) and thermal infrared (TIR).

- Burned areas = areas affected by fire within a certain time interval (example: MODIS MCD45, ESA Fire CCI); detection based on time series processing of near- and short-wave infrared optical data, looking for the effects of fire on vegetation.

How do active fires and burned areas relate?

Ideally, the accumulation of active fire detections over time would result in the identification of the whole burned area.

In reality, one needs to take into account two phenomena:

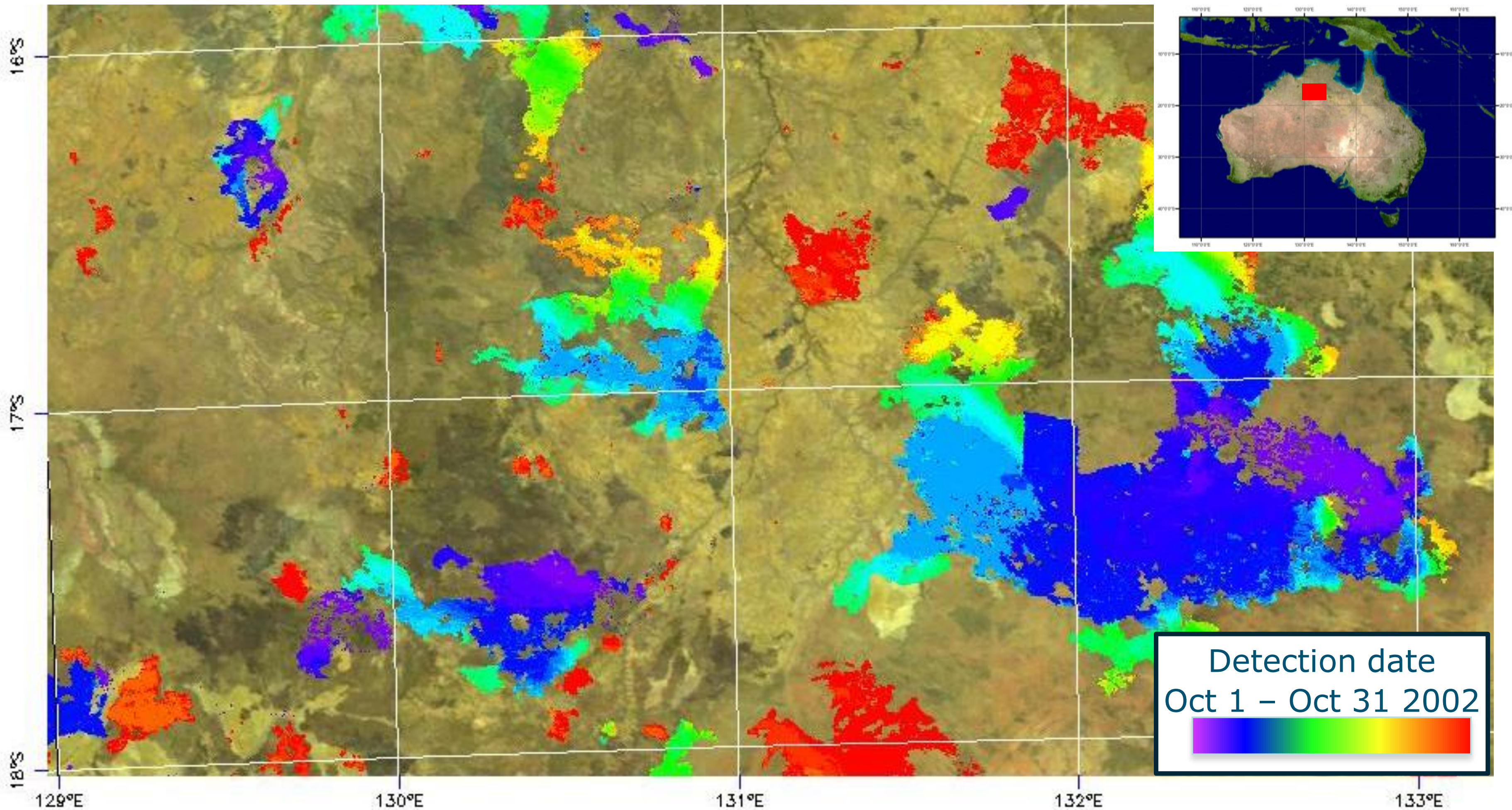
- Satellites can image an area only at discrete intervals (from hours to days); also, clouds and smoke can preclude the view and prevent the detection.
- The spatial resolution of thermal sensor is generally lower than visible/IR sensors, and small fires can trigger a detection:
    - In forest, ~100 m^2 of flames are sufficient for flagging a whole 1km^2 pixel as actively burning

How do active fires and burned areas relate?

Depending on the vegetation and fire characteristics, fires can have different outcomes, exemplified in the following examples:

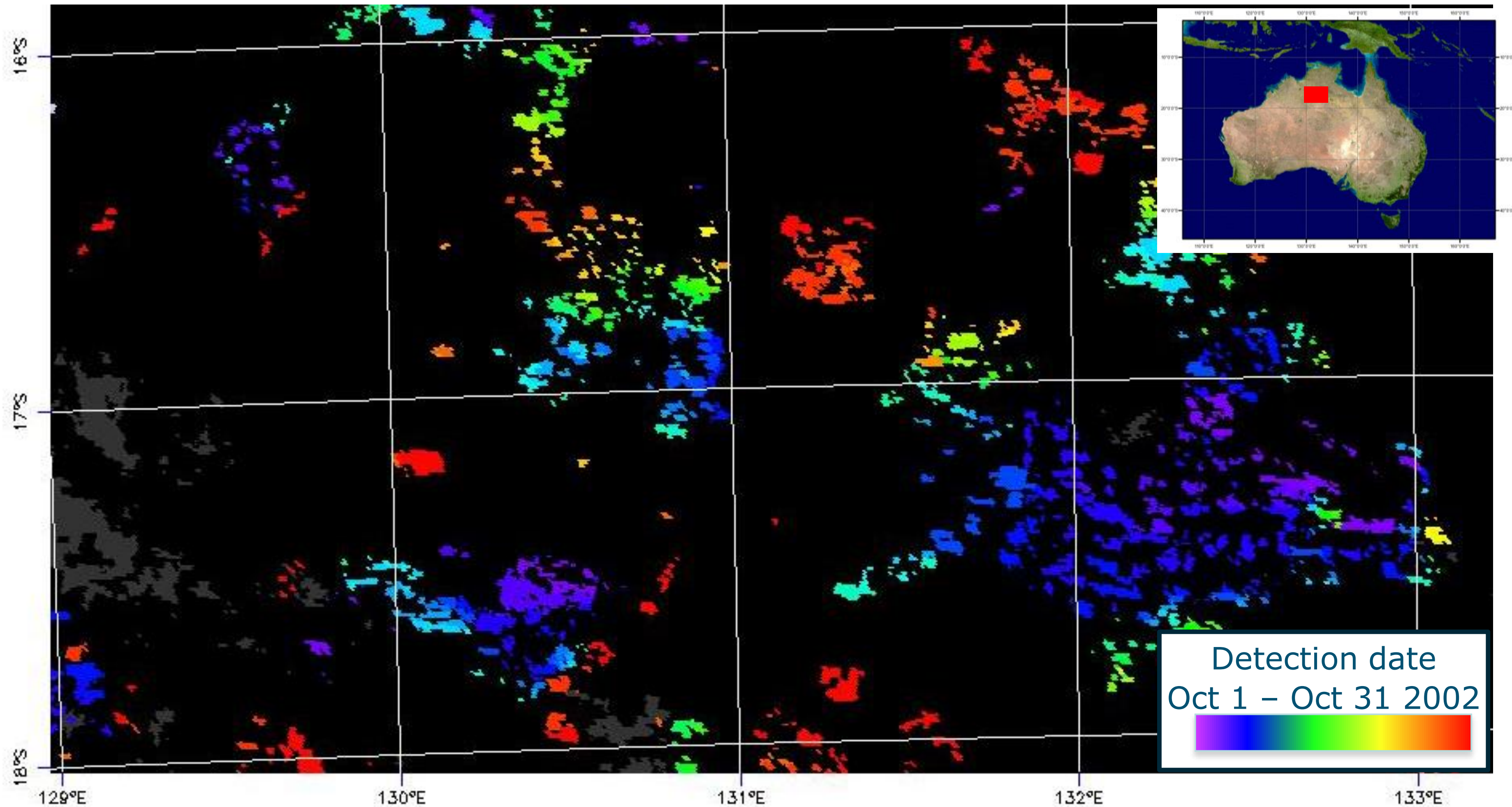
- In savannahs, large burned areas are underestimated by active fire products, because of fast-moving fire fronts (Australia example).
- In fragmented savannahs, there are small fires that can be detected as active fire but are too small to result in a burned area detection (Africa example).
- In forest ecosystems, fire fronts move slowly and are fully captured by the active fire product, but there is an overestimation due to the pixel size (Siberia example).
- Land-clearing fires do not result in a detectable burned area, because the fuel is burned in piles, but are detected as active fires (Amazon example).

Australia: Burned areas



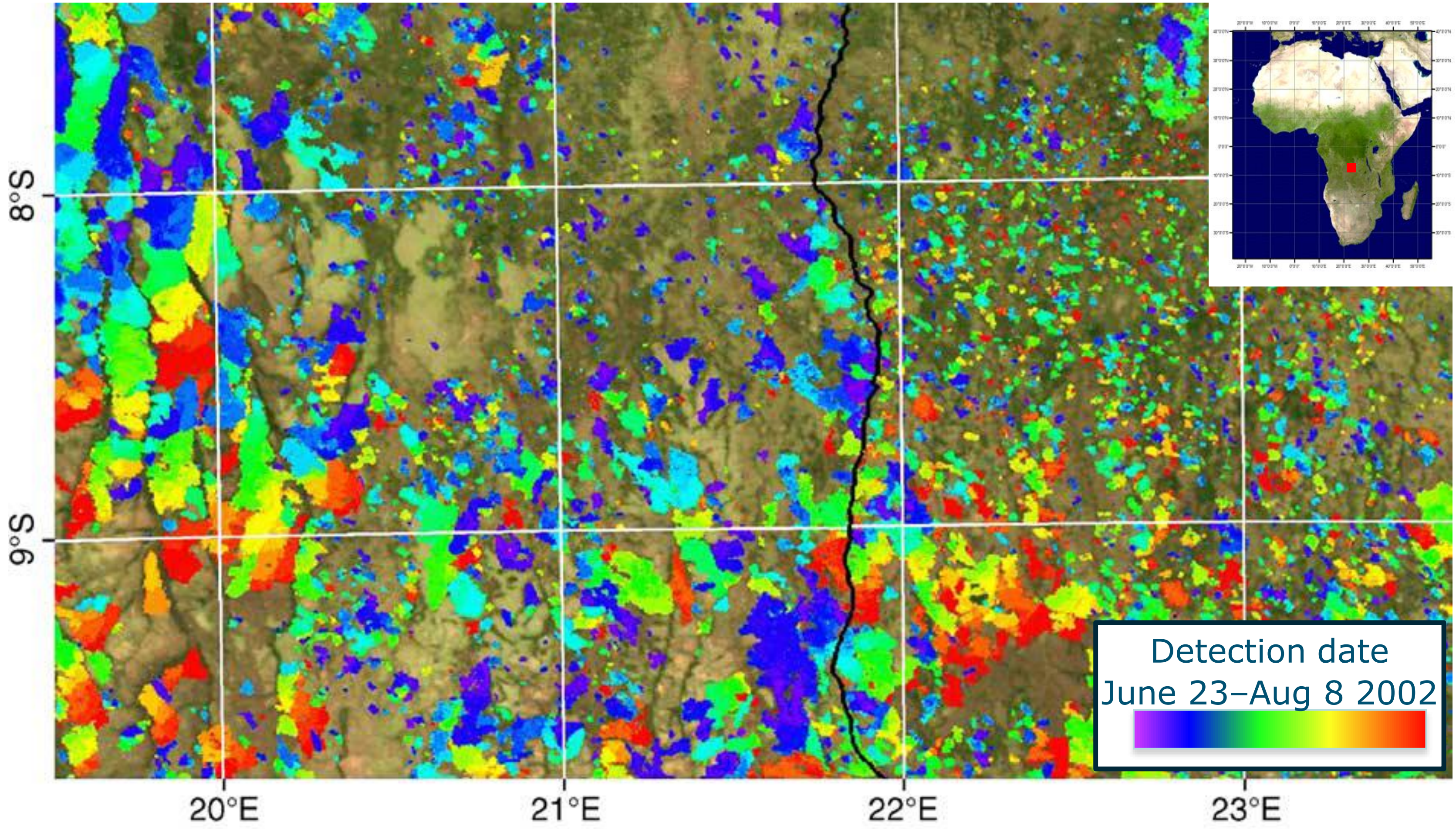
(Roy et al. 2005)

Australia: Active fires



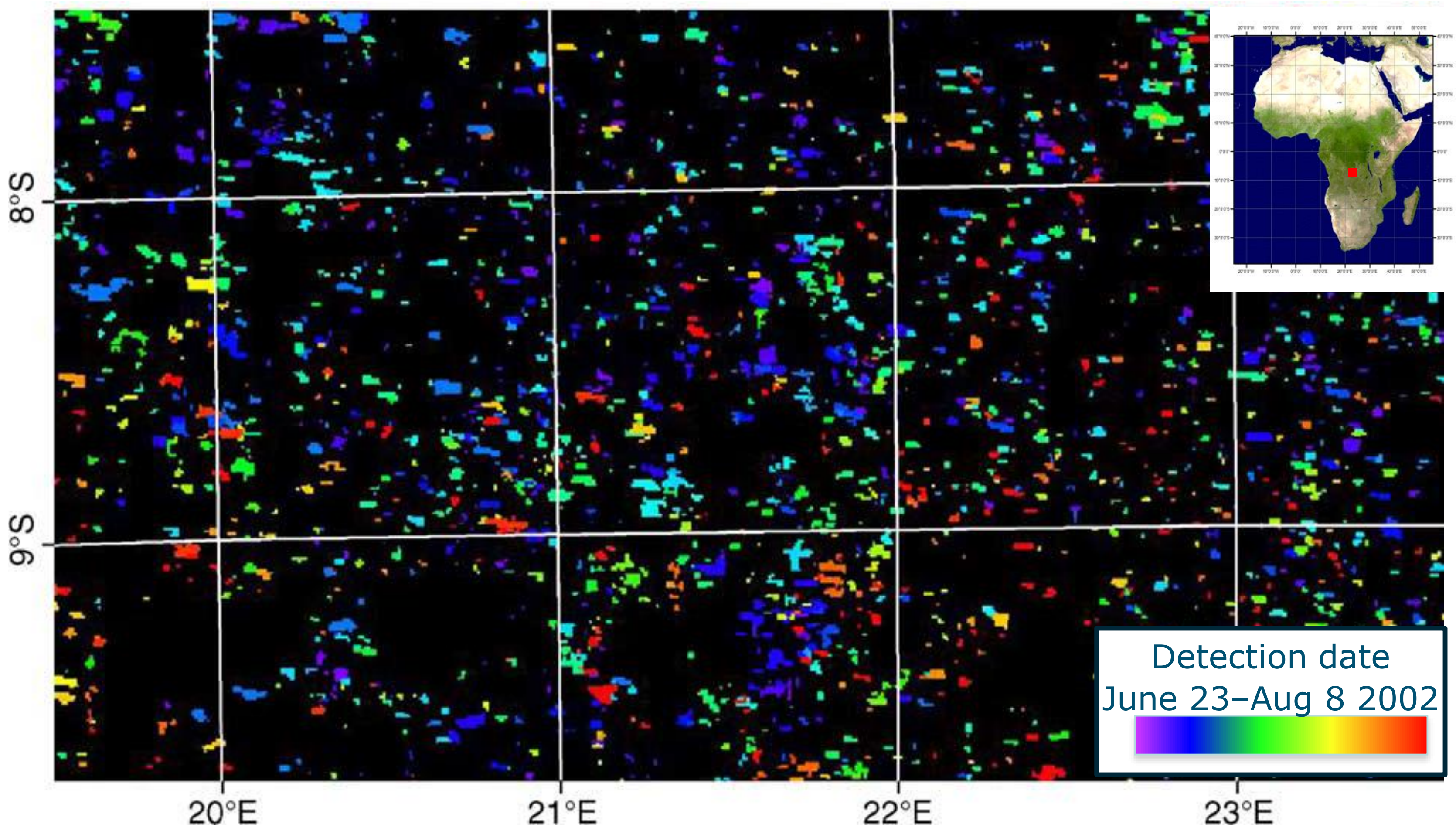
(Roy et al. 2005)

Southern Africa: Burned areas



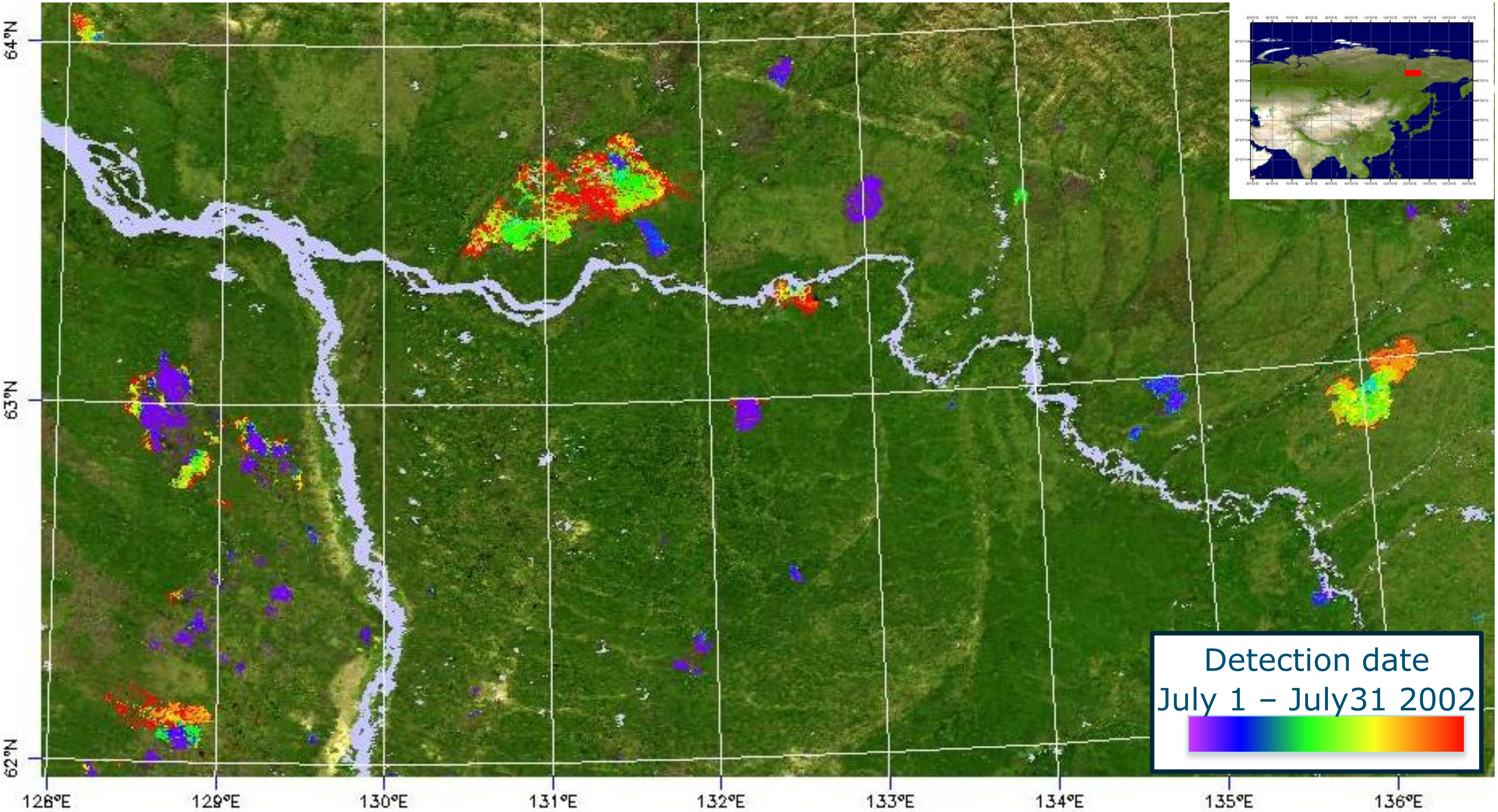
(Roy et al. 2005)

Southern Africa: Active fires



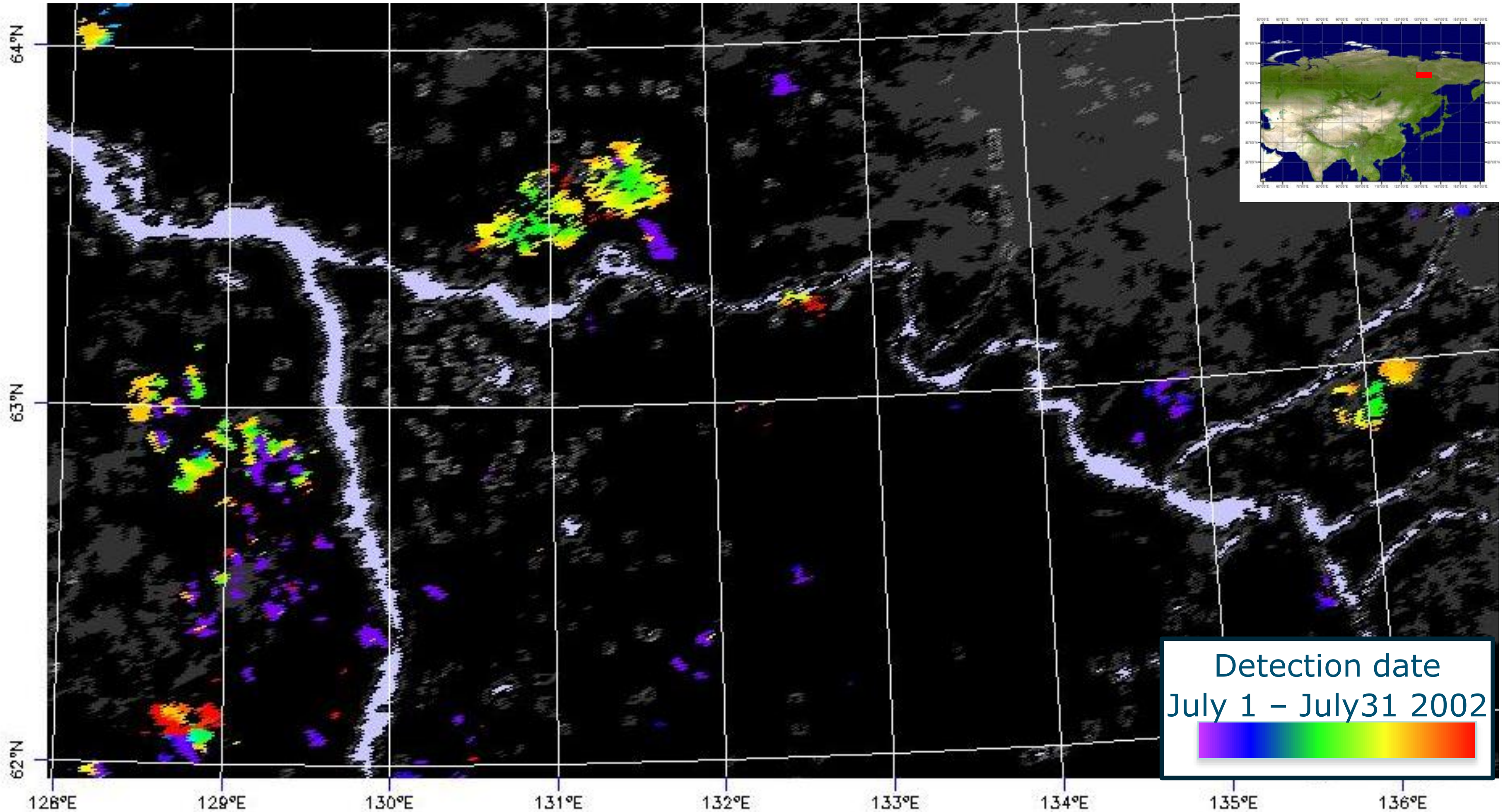
(Roy et al. 2005)

Siberia: Burned areas



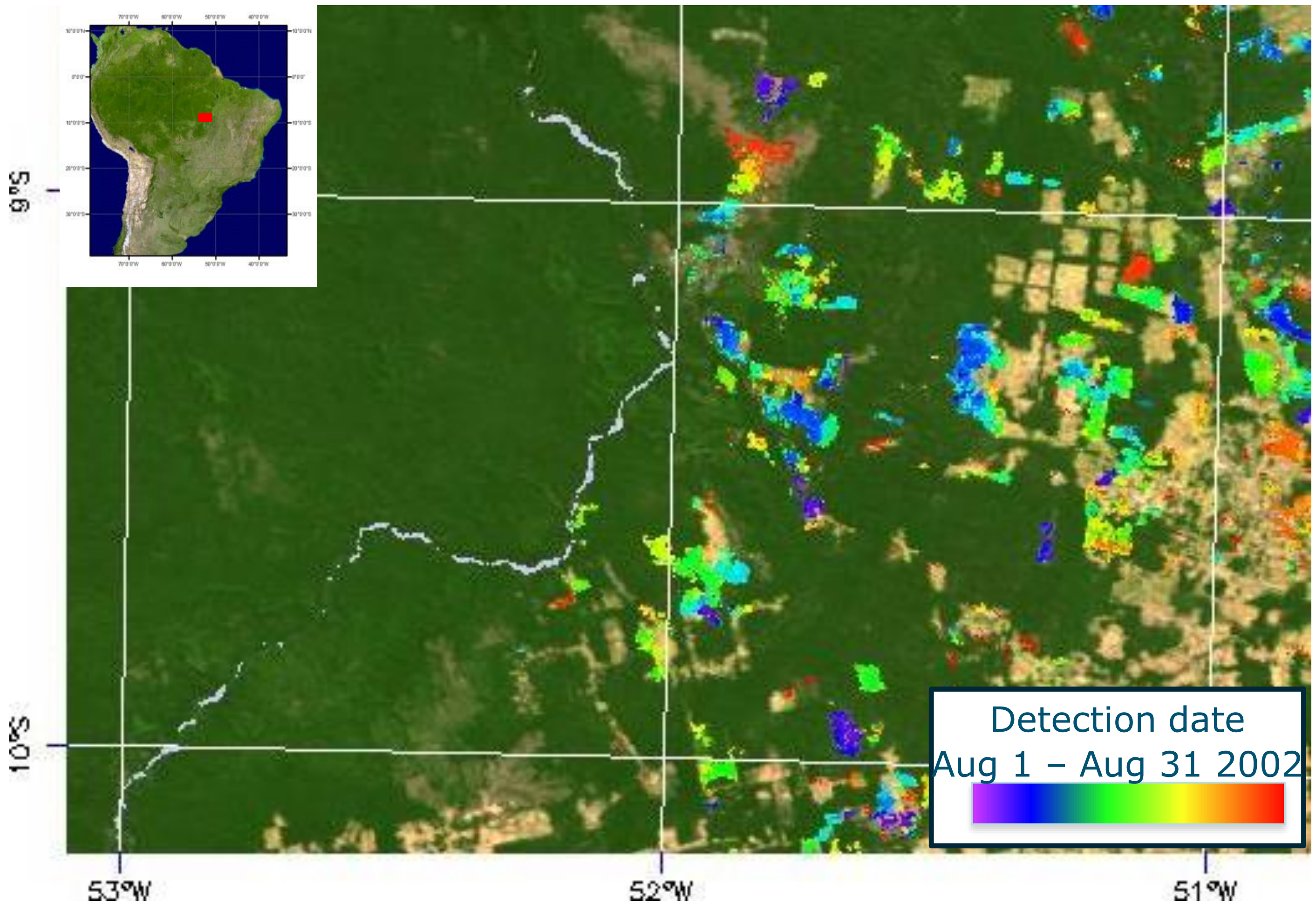
(Roy et al. 2005)

Siberia: Active fires



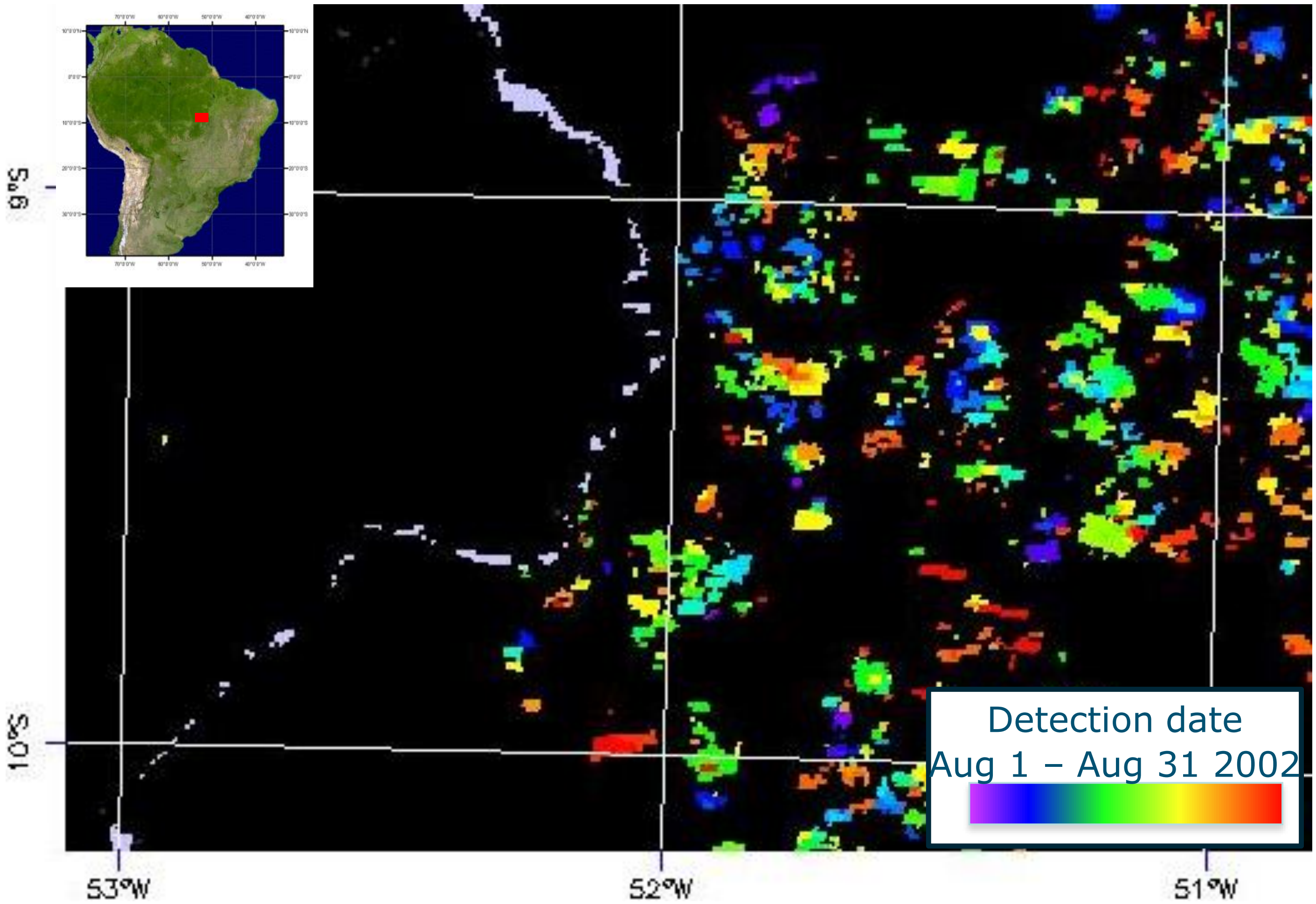
(Roy et al. 2005)

Amazonia: Burned areas



(Roy et al. 2005)

Amazonia: Active fires

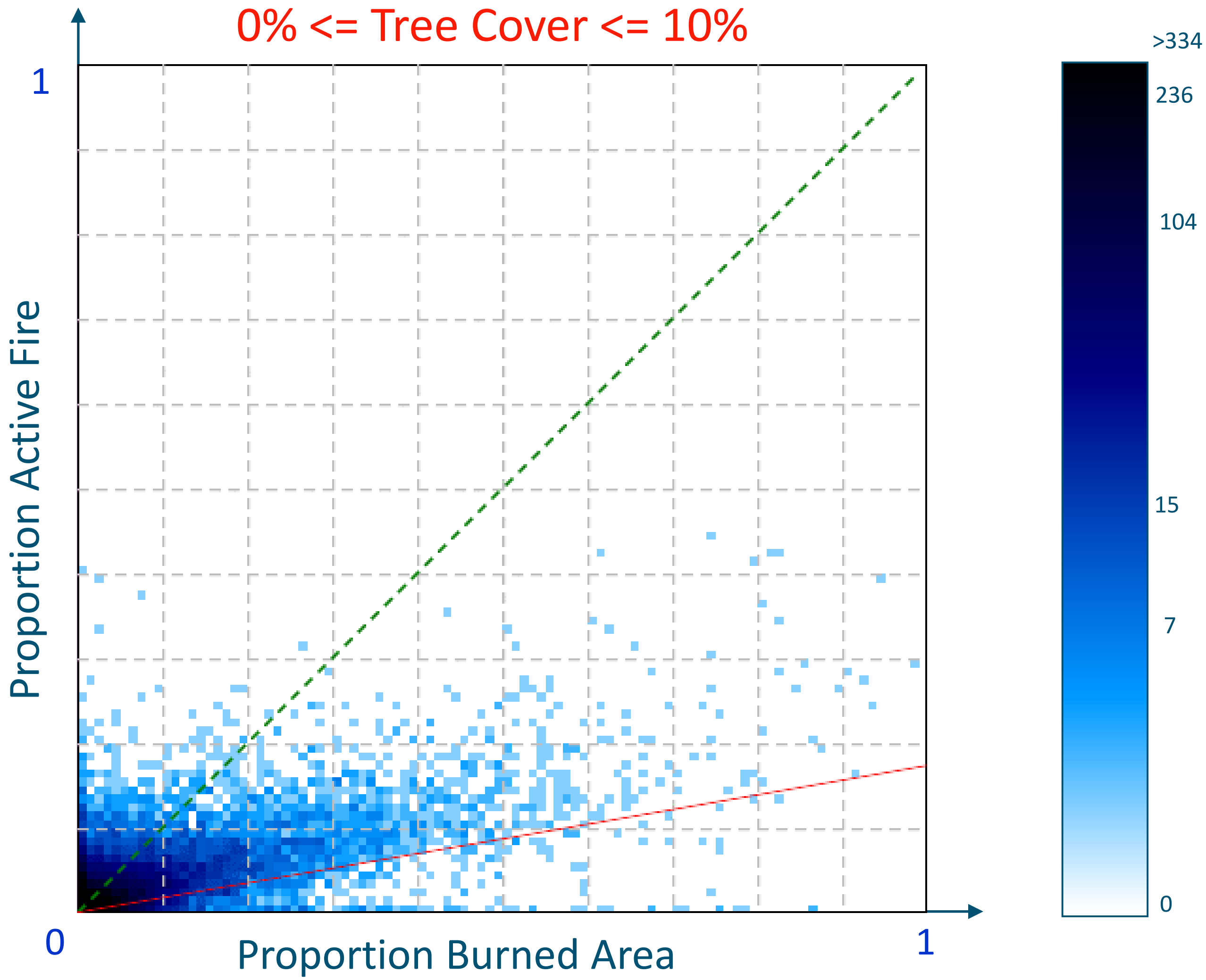


(Roy et al. 2005)

How do active fires and burned areas relate?

- The pattern is confirmed by systematic comparison of the global datasets.
- As the percentage of tree cover increases, **the ratio between active fire and burned area detection changes**, from more burned area detections than active fires in grasslands and savannas, to more active fire detections than burned area detections in very closed forest.

Active fires vs. burned areas in very open Savanna



61,523 cells

mean tree cover = 3.84 %

Slope = 0.173

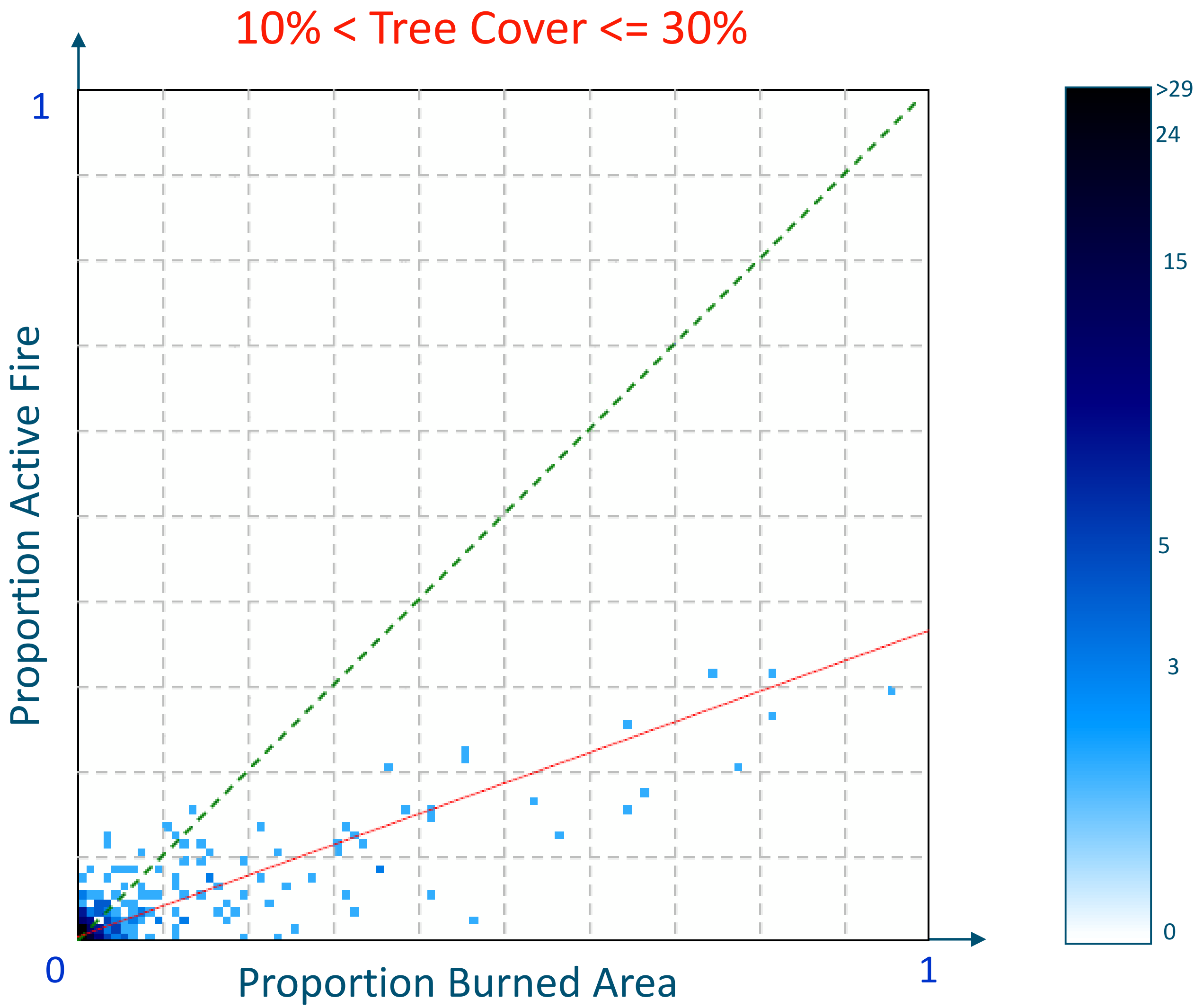
Intercept = 0.002

r = 0.71

Global

2001-2002

Active fires vs. burned areas in closed Savanna



417 cells

mean tree cover = 22.5 %

Slope = 0.359

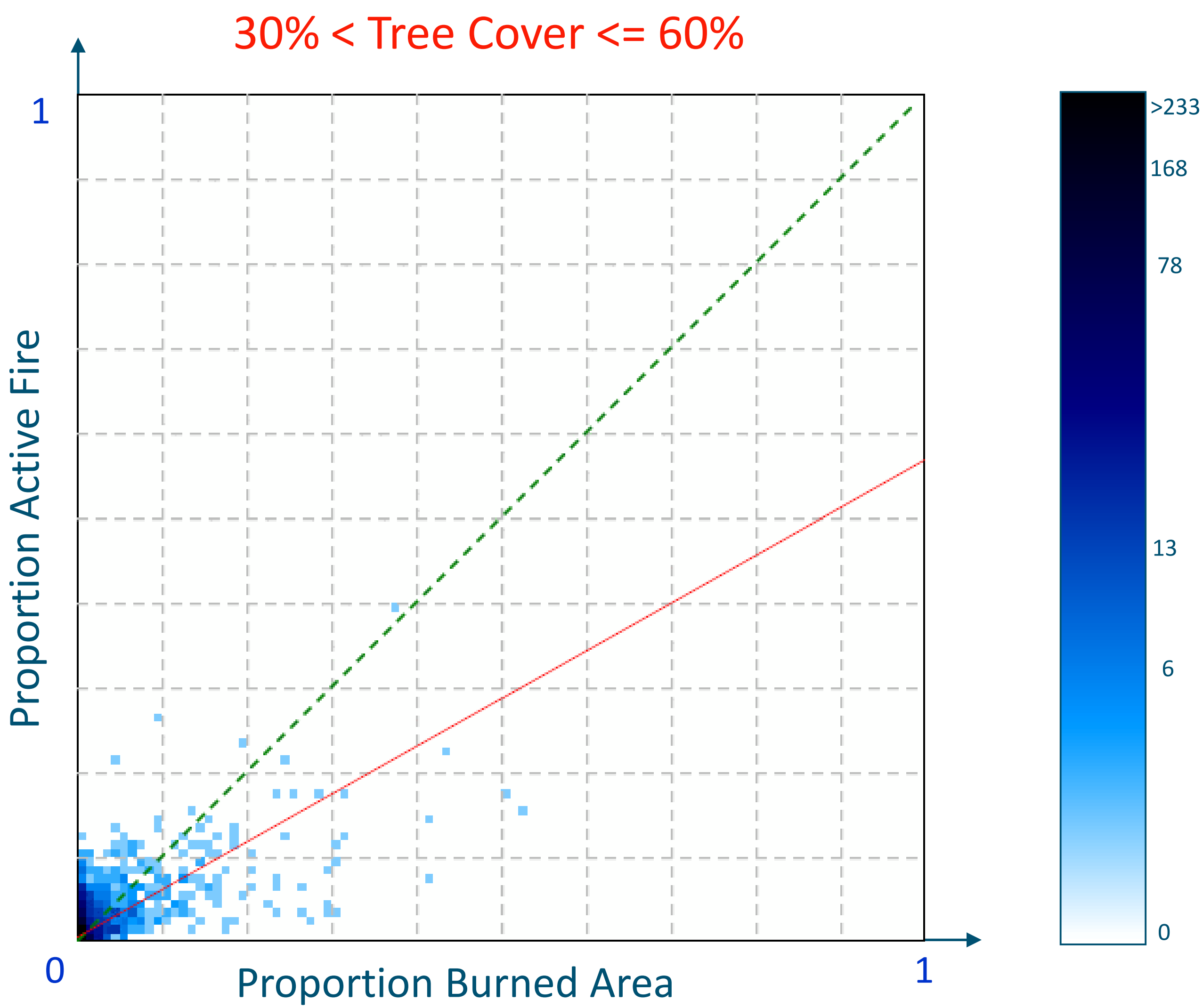
Intercept = 0.006

r = 0.87

Global

2001-2002

Active fires vs. burned areas in open forest



2,197 cells

mean tree cover = 43.2 %

Slope = 0.562

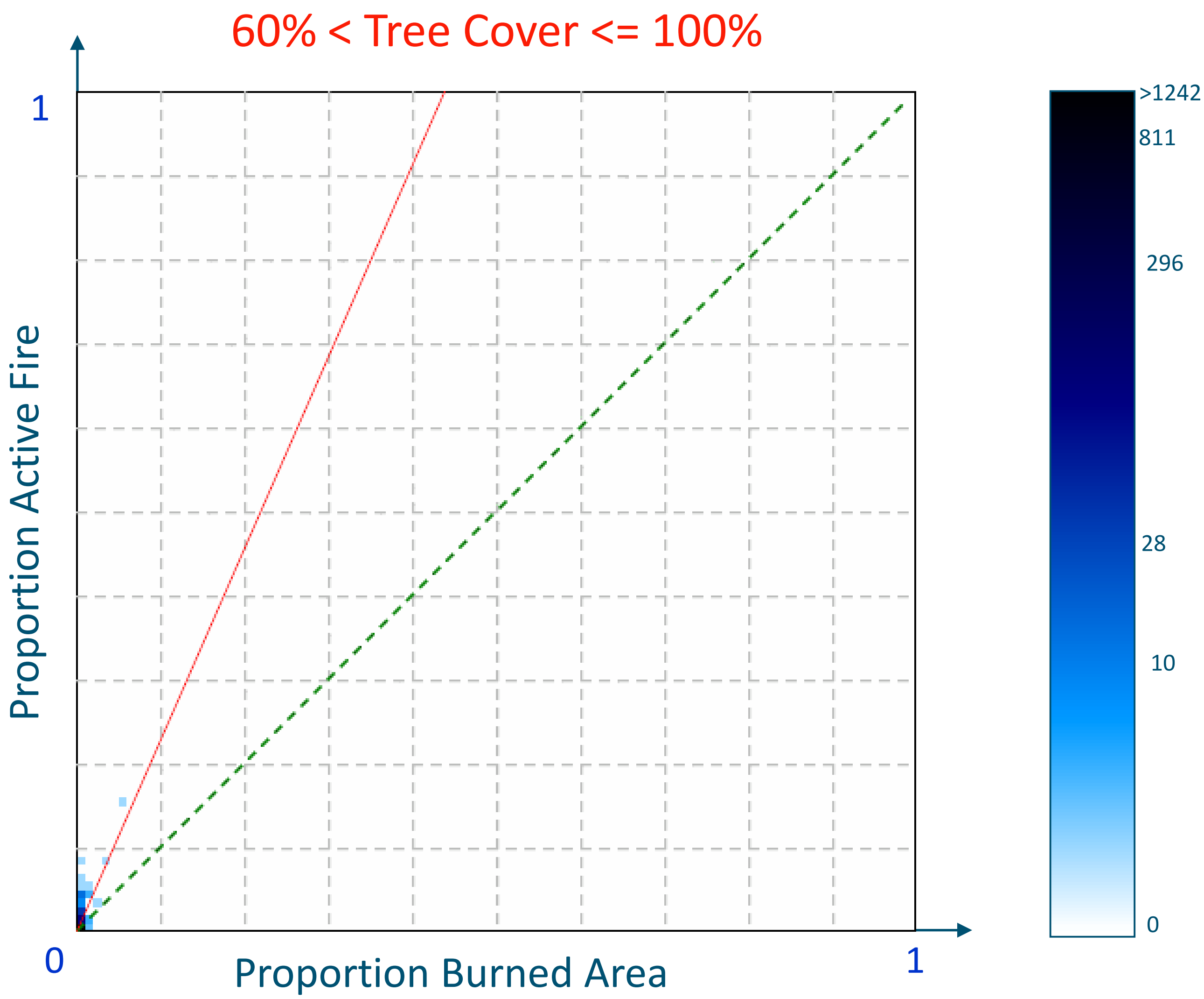
Intercept = 0.006

r = 0.65

Global

2001-2002

Active fires vs burned areas in closed forest



1,403 cells

mean tree cover = 76.2 %

Slope = 2.276

Intercept = 0.002

r = 0.67

Global

2001-2002

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Satellite data

- The nature of fire as nonpermanent land-cover change poses requirements on temporal sampling more strict than for other disturbances.
- Available sensors (tradeoff between spatial and temporal resolution):
  - Hyperspatial: 1 meter–10 meter pixel, available sporadically
  - Moderate / high: 10 meter–30 meter, available weekly/monthly
  - Coarse: over 100 meter, available daily

Satellite products

- Do we have data with the accuracy needed, e.g., mapping forest loss at ~ 1ha?
  - There are plenty of systematic fire products, but none at the moment with sufficient spatial resolution (not to mention the validation).
  - Some high resolution mapping systems exist (e.g., ESA- supported Landsat scale mapping in Mediterranean, EFFIS, MTBS) but are not systematic and are not in many countries that would need them.

Satellite products (1/2)

- Updated list of global and regional products

GOFC-Fire Fire Monitoring and Mapping Implementation Team. http://gofc-fire.umd.edu

- Active fire products

MODIS active fires (University of Maryland /NASA / NOAA) 2000–present

http://modis-fire.umd.edu (product information)

http://lance-modis.eosdis.nasa.gov/ (real time web-GIS visualization and distribution)

VIIRS active fires (University of Maryland /NASA / NOAA) 2012–present

http://viirsfire.geog.umd.edu

GOES WF-ABBA (University of Wisconsin/NOAA) 2000–present

http://cimss.ssec.wisc.edu/goes/burn/wfabba.html

Meteosat Second Generation (Eumetsat) 2004–present

http://landsaf.meteo.pt/

TRMM VIRS fire product (NASA) 1998–2005

ftp://disc2.nascom.nasa.gov/data/TRMM/VIRS_Fire/data/

World Fire Atlas (ESA) 1997–2012

http://due.esrin.esa.int/wfa/

Satellite products (2/2)

- Burned area products

  MODIS burned areas (Univ. of Maryland / South Dakota State Univ./ Univ. of Idaho / NASA) 2000-present

  http://modis-fire.umd.edu

  L3JRC (EC Joint Research Center) 1998-2007

  http://bioval.jrc.ec.europa.eu/products/burnt_areas_L3JRC/GlobalBurntAreas2000-2007.php

  Fire CCI (University of Alcala, ESA) under development, currently 2006-2008

  http://www.esa-fire-cci.org

- Emissions

  Global Fire Emissions Database (GFED3) - multi-year burned area and emissions 1997-present

  http://ess1.ess.uci.edu/%7Ejranders/data/GFED3/

  MACC-II (Monitoring Atmospheric Composition and Climate). Global fire analyses and estimates of emissions from fires. 2003-present

  http://www.gmes-atmosphere.eu/about/

Fire mapping on high resolution data

- This is is the standard procedure for generating validation datasets for coarse resolution products.
- The image classification and on-screen digitization requires minimally trained personnel.
  → Very accurate, but time consuming—prohibitive for systematic country scale mapping
- There are experimental projects for the systematic mapping at 30m scale; no global coverage available yet.

Visual interpretation of high resolution images

- Standard protocol: mapping the difference between two consecutive acquisitions
- Widely used for the accuracy and uncertainty assessment of the systematic products
- It can be cost-effective if targeted at selected areas for postfire assessment of events of particular importance

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IPCC emissions estimation

Back to bottom-up IPCC approach:

$$L_{fire} = A \times Mb \times Cf \times Gef$$

L = emission for each gas

A = area burned

Mb = fuel load

Cf = combustion factor

Gef = amount of gas released per unit of biomass consumed by the fire

Implementation of bottom-up approach

The bottom-up approach is linear, and it can easily be implemented in a GIS environment:

$$Lfire_i = A_i \times Mb_i \times Cf_i \times Gef_i$$

Where:

i is a generic burned area pixel, Ai is the area of the pixel, and Mb_i , Cf_i , Gef_i are the biomass load, combustion factor, and emission coefficients for that location.

Tier 1 emissions computation

A Tier 1, simple computation can be done with:

- Burned area from satellite products
- Tabular values from the IPCC guidelines, stratified by land-cover class, for:
  - Biomass (IPCC 2014, table 2.4)
  - Combustion completeness (table 2.6)
  - Emission factors (table 2.5)
- An example of step-by-step calculation is provided in the accompanying exercise section

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Error sources

Bottom-up approach:

$$Lfire = A \times Mb \times Cf \times Gef$$

- All terms of the equation are affected by errors.
- Satellite datasets have greatly reduced the uncertainty on global burned area estimates, but at local scale errors up to 50% have been reported.
- Biomass load and combustion factors are also poorly characterized in the literature.
- Emission factor tables compiled from previous studies often ignore the seasonal changes.

Workflow for Tier 1 assessment

Potential workflow for a Tier 1 assessment:

- Evaluate the accuracy of the global datasets for the area of interest, comparing them to free Landsat data.
- Use data from ground surveys to build a local table of biomass load for the area of interest whenever possible, instead of the reference values of IPCC (2006) table 2.4.
- Use the reference values for combustion factors and emission factors.

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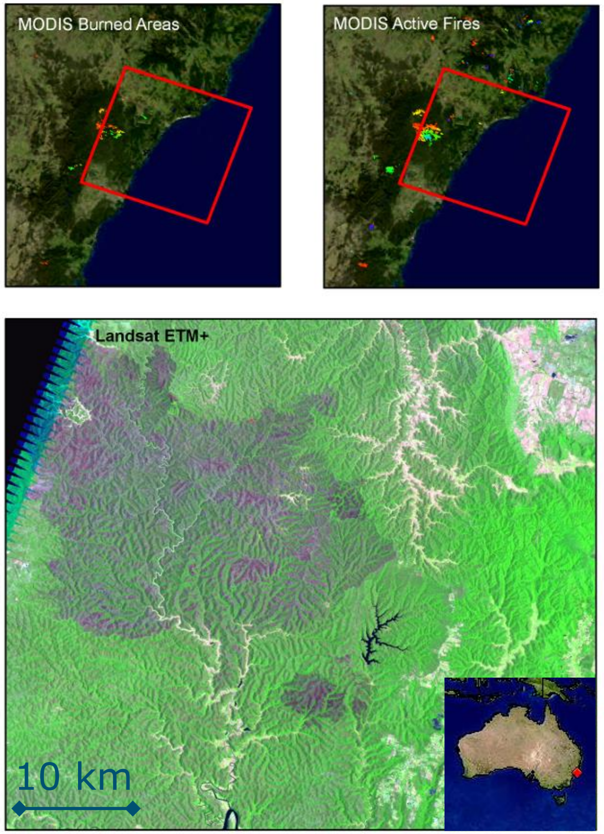
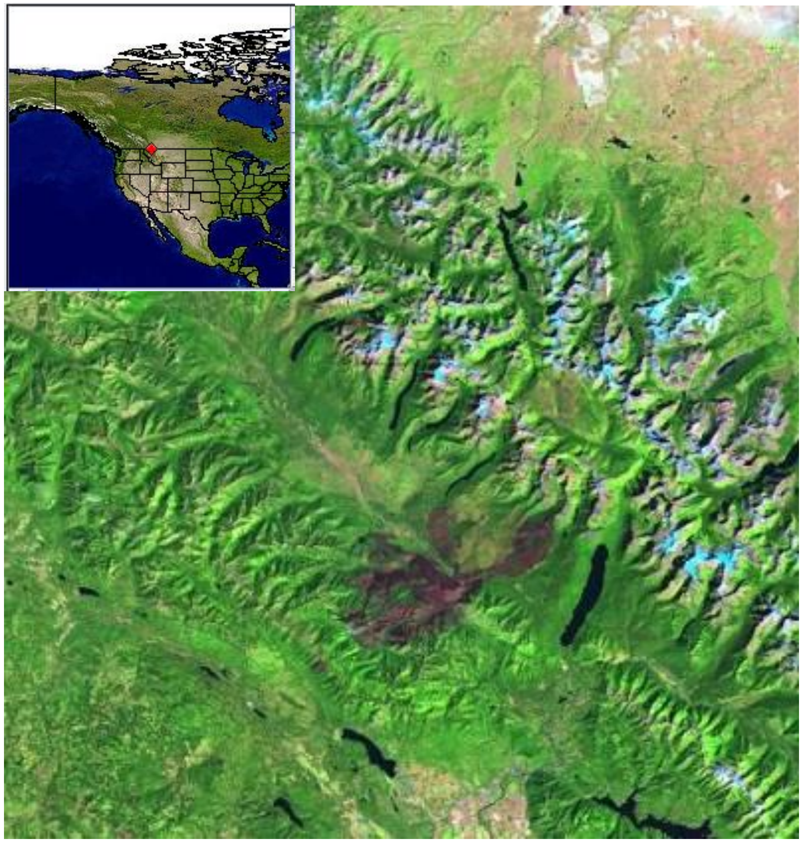
Using fire products for hotspot detection

- Identify areas where forest fires occurred, to guide acquisition of high resolution imagery.
- The mapping is refined in the high resolution imagery.



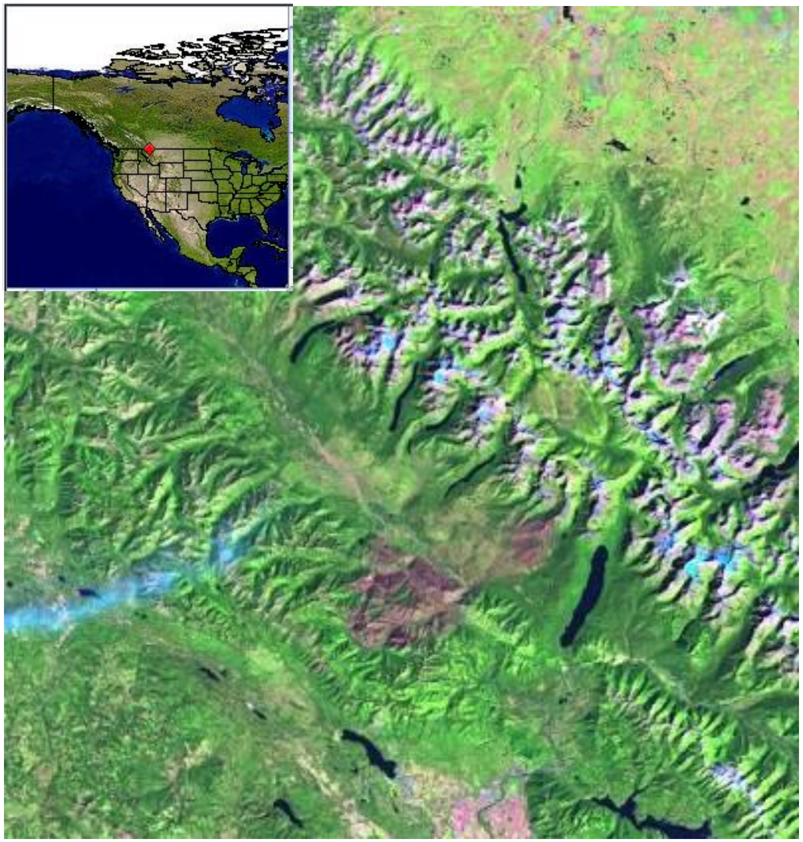
Satellite data for postfire characterization



2001

Conversion from forest to other land use after fire?

Satellite data for postfire characterization

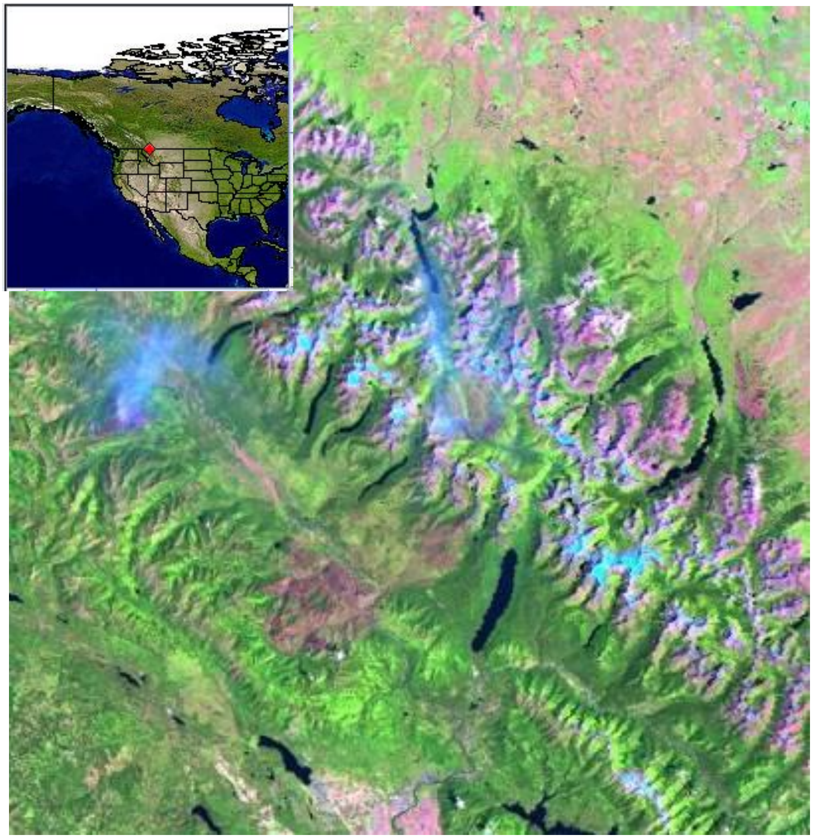


2002

Conversion from forest to other use after fire?

One year later: no.

Satellite data for postfire characterization



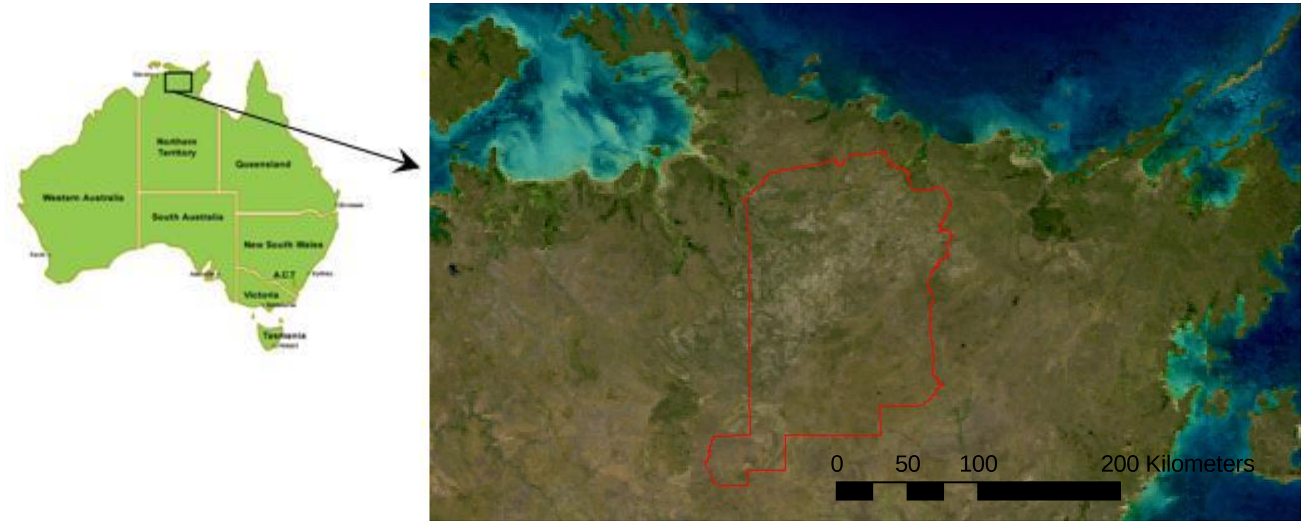
2003

Conversion from forest to other use after fire?

One year later: no.
Two years later: no.

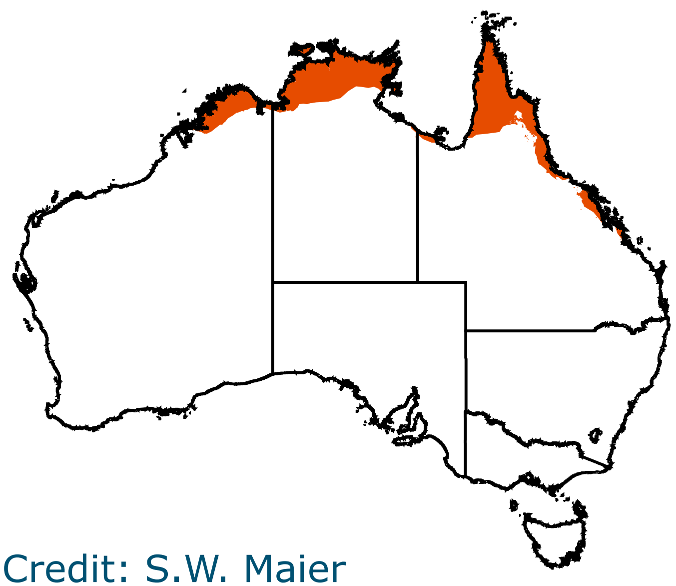
Fire management

- What is forest? Woody Savanna, with tree cover between 10% and 30% can be considered
- Change in total annual emissions by managing fire and changing the seasonality (early versus late fires)
- Example: WALFA in Northern Australia



Carbon farming initiative (CFI)

- Australia introduced a carbon price on 1 July 2012 (fixed at 23 A$/$t_{CO2e}$ for 2012/13).
- The CFI allows farmers and land managers to earn carbon credits by storing carbon or reducing greenhouse gas emissions on the land.
- CFI includes methodology for accounting emissions (non-CO_2) from savanna burning in high rainfall areas (>1000mm/a).



Credit: S.W. Maier

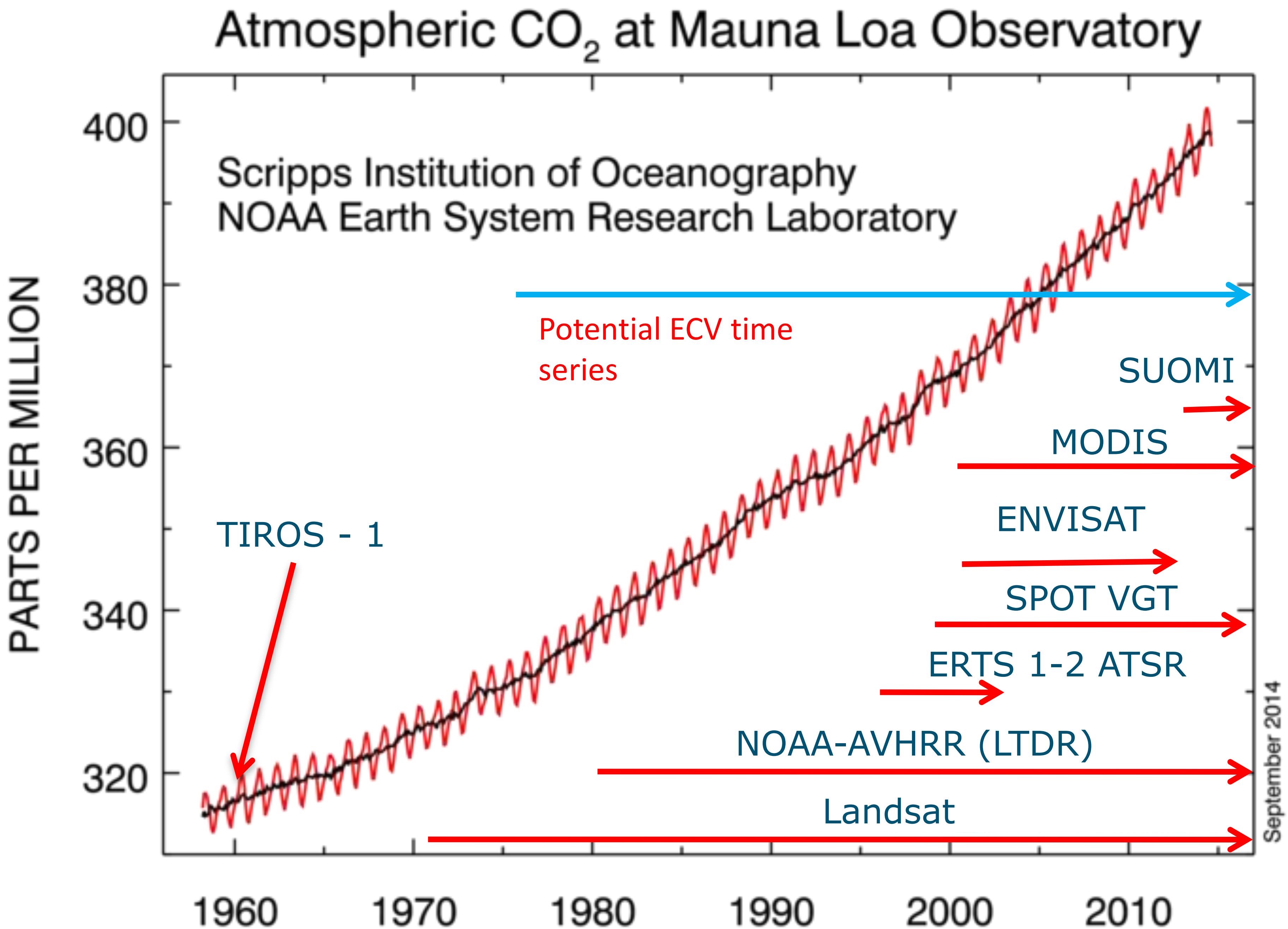
Savanna burning methodology (>1000mm/a)

Objective: Reduce emissions through early dry season (EDS) prescribed burning:

- Vegetation type map ≤ 250m
- Burnt area 5 years prebaseline ≤ 1km
- Burnt area 10 years baseline ≤ 1km
- Burnt area project years ≤ 250m
- Accuracy burnt area > 80%, assessed using (random) aerial observations
- Fuel load derived from time since last fire
- Combustion completeness (EDS vs LDS)
- Emission factors dependent on fuel type only, not season (Maier et al. 2012)

Long-term data records

- Essential climate variables, defined by GCOS (under WMO)
- Integration of existing data sources
- Intercalibration of existing thematic products
- International cooperation for harmonization of future products
- Potential for series starting in 1980, with local test dataset with Landsat data from 1970s



Atmospheric CO_2 at Mauna Loa Observatory
Scripps Institution of Oceanography
NOAA Earth System Research Laboratory
PARTS PER MILLION
400
380
360
340
320
1960
1970
1980
1990
2000
2010
Potential ECV time series
SUOMI
MODIS
ENVISAT
SPOT VGT
ERTS 1-2 ATSR
NOAA-AVHRR (LTDR)
Landsat
TIROS - 1
September 2014

Long-term data records

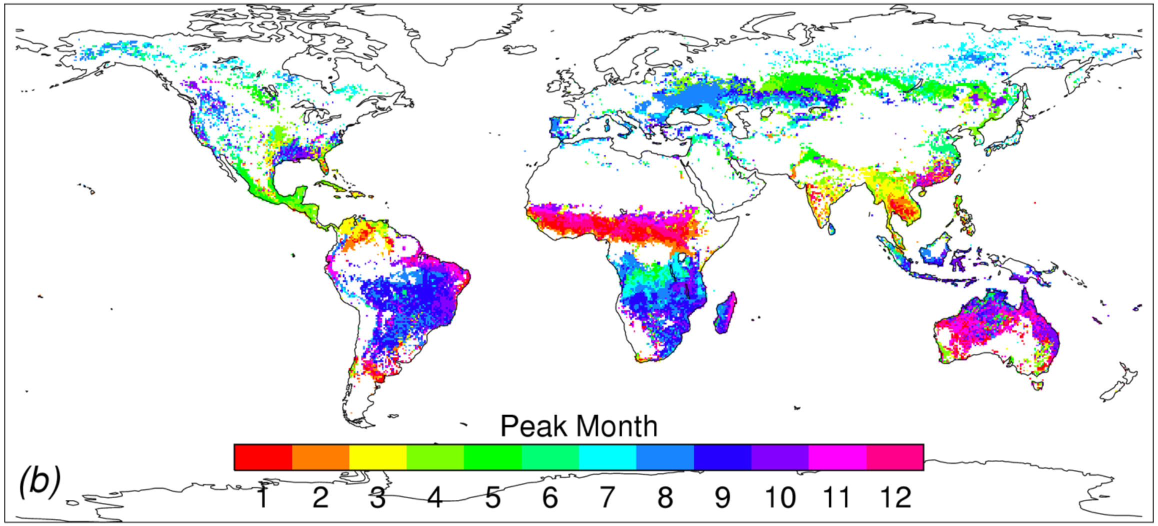
ECVs essential for answering the fundamental science question of the baseline of fire activity:

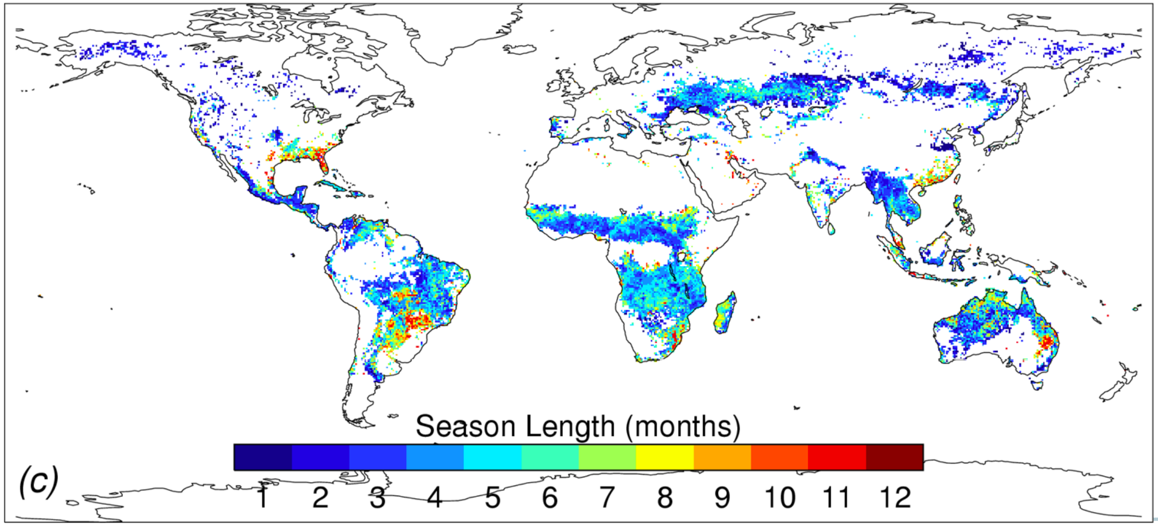
- Fire assessment at global, continental, and country levels
- Analysis of fire regime interannual variability

Main issue: work needed for calibration and validation of the products

Luigi Boschetti and David Roy, 2008

Climatological fields



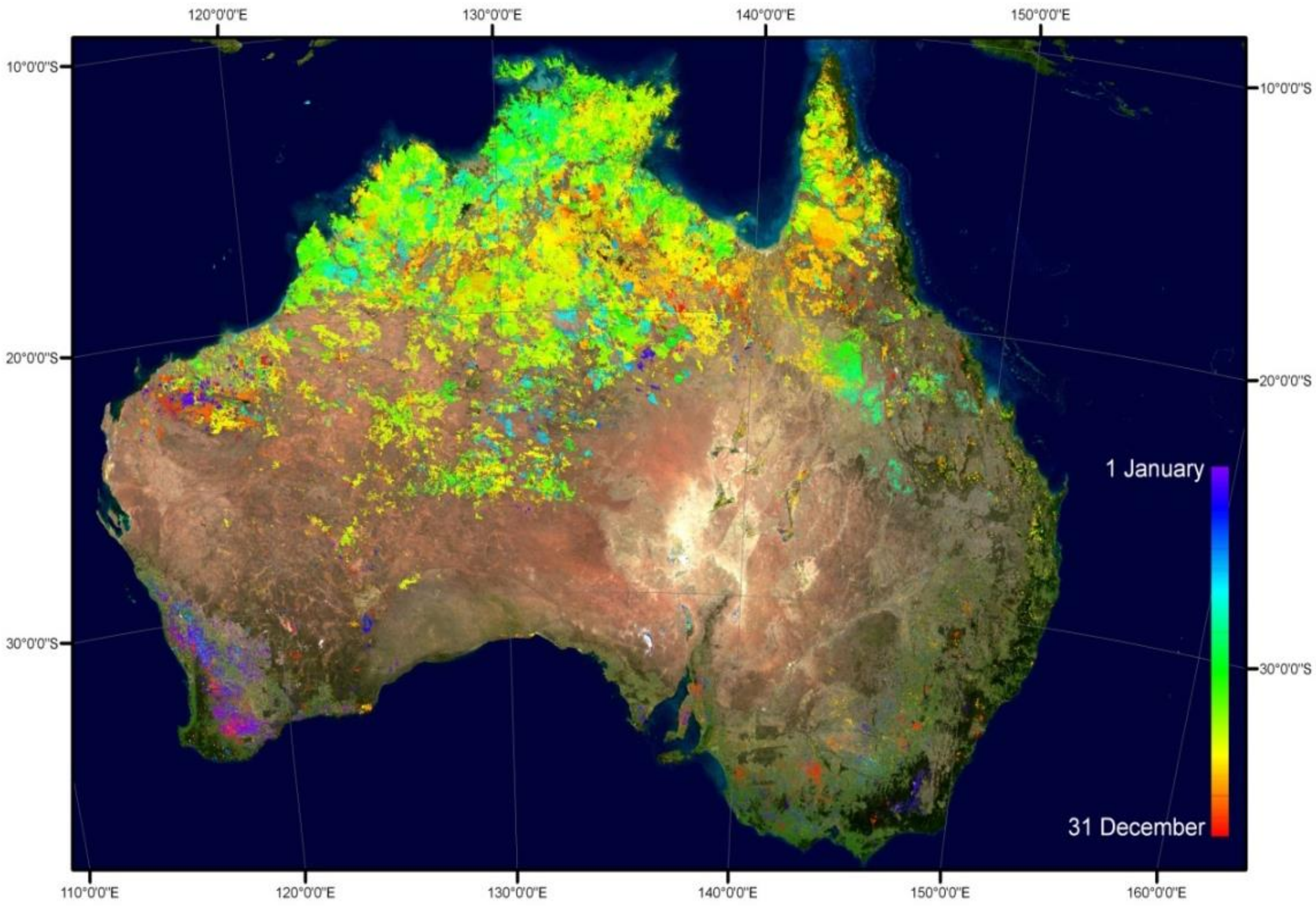


Climatological fields derived from the first five years of Terra MODIS fire observations (November 2000 to October 2005)

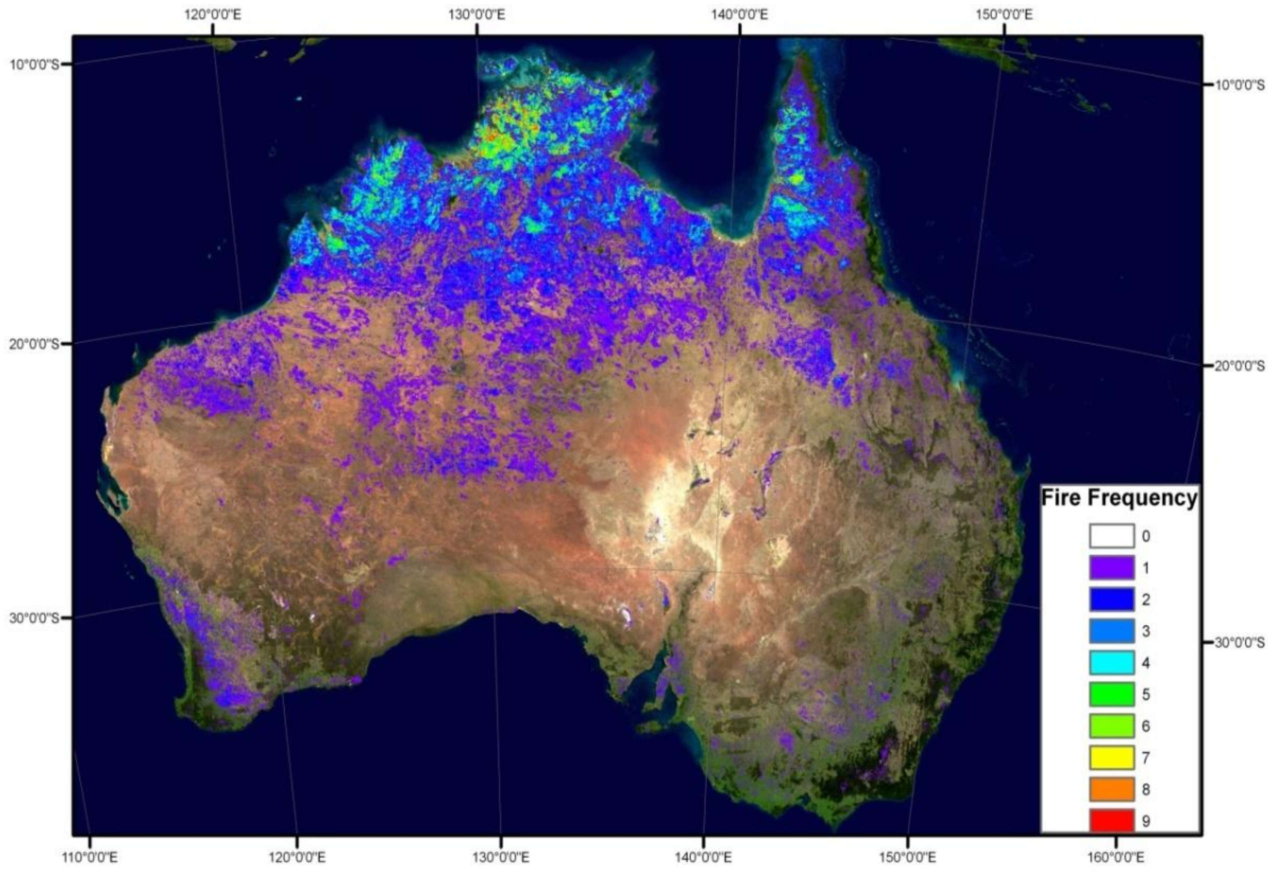
(b) Month of maximum climatological fire activity
(c) Fire season length

(Source: Giglio et al. 2006)

Median day of burning from eight years of MODIS burned area data



Fire frequency from eight years of MODIS burned-area data



In Summary

- Monitoring of fires requires an understanding of the process of fire in forest systems (either as an ecological change agent, a disturbance, a forest management tool, or as a process associated with land cover conversion)
- There are different approaches and objectives to monitor fires in the context of REDD+
    - Pre-fire (early warning systems)
    - Active fire (hotspot satellite data)
    - Post-fire (burned area estimates)
- Calculation of emissions from biomass burning follows the Bottom-up IPCC approach: $L_{fire} = A \times M_b \times C_f \times G_{ef}$ (IPCC, 2006, AFOLU GL, section 2.4)

Country examples and exercises

Country examples (regions)

- Africa: Burned areas and active fires maps
- Amazonia: Burned areas and active fires maps

Exercise

- Using available fire datasets to estimate GHG emissions from biomass burning in the national contexts for Botswana and Brazil.

Recommended modules as follow-up

- Module 2.7 to continue with estimation of uncertainties
- Module 2.8 to learn more about evolving technologies for monitoring of forest-area changes, carbon stocks, and emissions
- Modules 3.1 to 3.3 to proceed with REDD+ assessment and reporting

References

- Boschetti, L. and Roy, D. Defining a fire year for reporting and analysis of global interannual fire variability. *Journal of Geophysical Research: Biogeosciences,* 113: G3. DOI: 10.1029/2008JG000686.
- IPCC 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Volume 4: Agriculture, Forestry and Other Land Use. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html (Often referred to as IPCC AFOLU GL)
- GFOI (Global Forest Observations Initiative). 2014. *Integrating Remote-sensing and Ground-based Observations for Estimation of Emissions and Removals of Greenhouse Gases in Forests: Methods and Guidance from the Global Forest Observations Initiative*. (Often GFOI MGD.) Geneva, Switzerland: Group on Earth Observations, version 1.0. http://www.gfoi.org/methods-guidance/.
- Giglio et al. 2006. Global estimation of burned area using MODIS active fire observations. *Atmos. Chem. Phys.*, 6, 957–974.
- Giglio, L., J. T. Randerson, G. R. van der Werf, P. S. Kasibhatla, G. J. Collatz, D. C. Morton, and R. S. DeFries. 2010. "Assessing Variability and Long-Term Trends in Burned Area by Merging Multiple Satellite Fire Products." *Biogeosciences* 7: 1171–1186. doi:10.5194/bg-7-1171-2010.

- GOFC-Fire Implementation Team Portal. http://gofc-fire.umd.edu/.
- GOFC-GOLD (Global Observation of Forest Cover and Land Dynamics). 2014. *Sourcebook* (*A Sourcebook of Methods and Procedures for Monitoring and Reporting Anthropogenic Greenhouse Gas Emissions and Removals Associated with Deforestation, Gains and Losses of Carbon Stocks in Forests Remaining Forests, and Forestation*). Netherlands: GOFC-GOLD Land Cover Project Office, Wageningen University. http://www.gofcgold.wur.nl/redd/index.php.
- Korontzi, S., McCarty, J., Loboda, T., Kumar, S. and Justice, C. 2006. Global distribution of agricultural fires in croplands from 3 years of Moderate Resolution Imaging Spectroradiometer (MODIS) data. *Global Biogeochemical Cycles*, 20. doi: 10.1029/2005GB002529. issn: 0886-6236.
- Meyer, C.P. et al. 2012. Direct measurements of the seasonality of emission factors from savanna fires in northern Australia. *Journal of Geophysical Research*. 117, D20305, doi:10.1029/2012JD017671
- NASA Science Visualization Studio. Visualizations by Lori Perkins on October 18, 2011. Australia Fire Observations and MODIS NDVI http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=3871
- Roy, D.P., Frost, P., Justice, C., Landmann, T., Le Roux, J., Gumbo, K., Makungwa, S., Dunham, K., Du Toit, R., Mhwandagara, K., Zacarias, A, Tacheba, B., Dube, O., Pereira, J., Mushove, P., Morisette, J., Santhana Vannan, S., Davies, D., 2005, The Southern Africa Fire Network (SAFNet) regional burned area product validation protocol, International Journal of Remote Sensing, 26:4265-4292.

- Seiler, W. and Crutzen, P. J.: Estimates of gross and net fluxes of carbon between the biosphere and atmosphere from biomass burning, Clim. Change, 2, 207–247, 1980.
- van der Werf, G. R., J. T. Randerson, L. Giglio, G. J. Collatz, M. Mu, P. S. Kasibhatla, D. C. Morton, R. S. DeFries, Y. Jin, and T. T. van Leeuwen. 2010. "Global Fire Emissions and the Contribution of Deforestation, Savanna, Forest, Agricultural, and Peat Fires (1997–2009)." *Atmospheric Chemistry and Physics* 10: 11707–11735. doi:10.5194/acp-10-11707-2010.
- UNFCCC. 2001. Decision II/CP.7. The Marrakesh Accords. http://unfccc.int/resource/docs/cop7/13a01.pdf