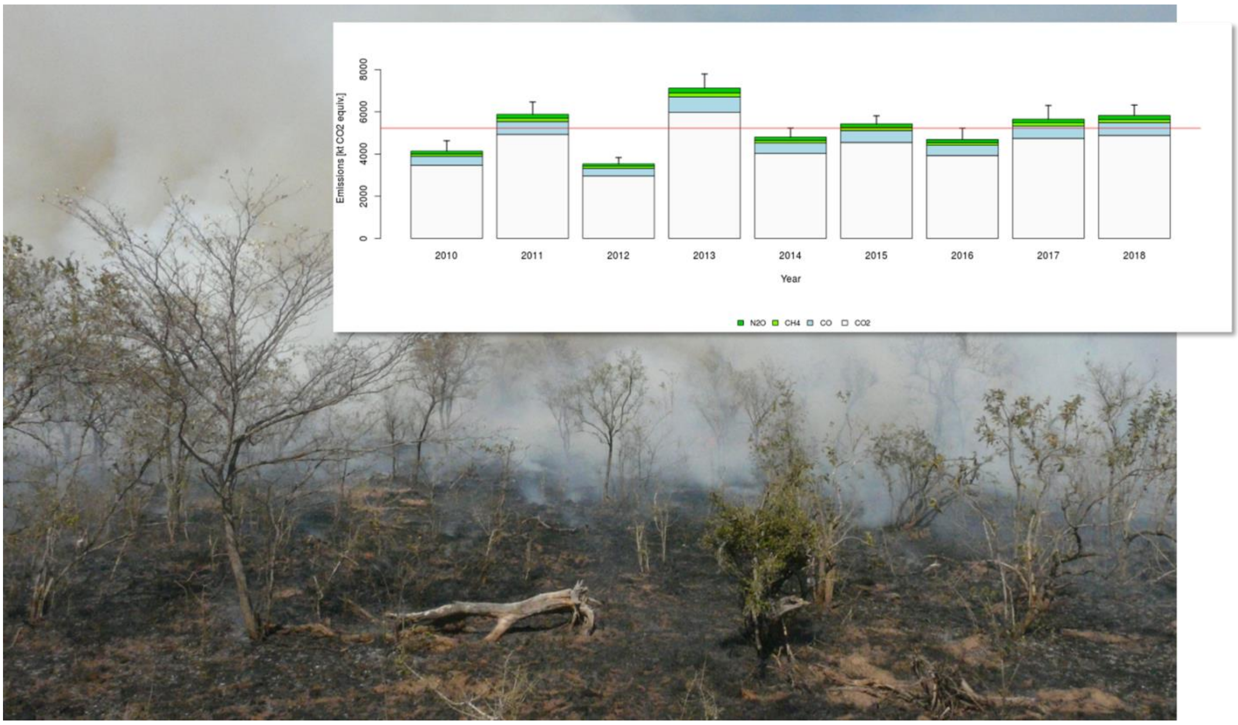
firemaps.net

White Paper:

Estimating emissions from fires in firemaps.net



ZEBRIS

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
FC	Fuel Consumption
FCDB	Fuel Consumption Database
FRE	Fire Radiative Energy
FRP	Fire Radiative Power
FWI	Fire Weather Index
GCF	Green Climate Fund
GHG	Greenhouse Gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
IPCC	Intergovernmental Panel on Climate Change
MODIS	Moderate Resolution Imaging Spectrometer
NASA	National Aeronautics and Space Administration
RS	Remote Sensing
PROFIAB II	Développement des Espaces Economiques et Naturels Taï et Comoé
USGS	United States Geological Service
UNFCCC	United Nations Framework Convention on Climate Change

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1 SUMMARY

In this white paper, we describe the methods used for estimating smoke emissions from fires in firemaps.net and show how practical applications for reducing greenhouse gas emissions from fire can be implemented using the tools provided by firemaps.net.

Our method is based on direct observation of the actively burning fire using satellites observing Earth with infrared sensors. These sensors are able to measure the heat emitted from fires. The amount of heat released during a fire is proportional to the amount of biomass burned, and biomass burned in turn is proportional to emissions of greenhouse gases and other smoke constituents. Using this method therefore offers an opportunity for directly deriving fuel consumption and emissions from remote sensing data.

The paper describes the estimation model and data used to derive fuel consumption from multiple satellite observations of active fires and burned areas, and the conversion of fuel consumption to smoke emissions. A comparison to field data is also provided. A detailed discussion of the achieved accuracy and sources of uncertainties is provided in the annex.

In the third section we describe practical applications with a focus on savanna ecosystems, first discussing the role of fire and CO_2 and Non-CO_2 greenhouse gas fluxes in savannas. A good understanding of fire regimes in potential project areas is required to plan for mitigation projects. Hence the role of establishing a fire emissions baseline for planning of emission reduction activities is described. Shifting of burning patterns has been shown to be an option to achieve reductions in fire emissions. We show how this can be planned, implemented and documented in firemaps.net with examples from West Africa and Brazil. Apart from directly reducing fire emissions, improved fire management, e.g. through using prescribed burning, can also help to increase carbon stocks when fire intensities are managed. How this can be done will be a key topic in a forthcoming white paper. Finally we point out how firemaps.net information products can help building a proposal to acquire funding through mechanisms such as the green climate fund.

2 INTRODUCTION

Bush, forest and peat fires cause substantial greenhouse gas and smoke emissions. According to recent estimates, carbon emissions from fire may amount to about 6% of carbon emissions from industrial sources when not counting the amount of emissions that are offset by subsequent regrowth (*1*). As an example, the Indonesian peat fires in September/October 2015 had higher carbon emissions than the EU's fossil fuel emissions over the same period (*2*) and it has been estimated that the smoke pollution caused over 100.000 premature deaths across the region (*3*) and had a substantial economic impact.

Fire managers and policy makers need to quantify smoke emissions of landscape fires, and to assess environmental and economic damage from fires. Information on past and ongoing fires is needed to efficiently allocate resources for fire management. Reducing emissions from fires can also present economic opportunities through carbon financing, e.g. the green climate fund. Activities supporting emission reductions through improved fire management can achieve substantial benefits in terms of avoided emissions. To effectively prove and monitor these savings, a remote sensing based solution is needed.

Current satellite sensors and their often freely available data provide opportunities to substantially improve current methods for quantitative evaluation of actively burning fires through higher spatial and/or temporal resolution.

In this white paper, we describe the methods developed by firemaps.net for the implementation of an efficient approach to monitor and quantify emissions from fires taking advantage of the latest science and technology.

3 ESTIMATION OF GREENHOUSE GAS EMISSIONS

3.1 Methods

Calculation of emissions of gases and particulate matter is complicated due to the volatile and heterogeneous nature of fire, and therefore uncertainties are high. Moreover, the main parameters of interest are not easily obtained in the field for validation.

Emissions from fires are commonly estimated from the amount of biomass burned, which is then multiplied with a specific emission factor for each smoke constituent (i.e. gas or particulate matter).

Biomass burned or fuel consumption can be derived through multiplication of the burned area with the fuel load (i.e. the biomass available for burning) and the combustion completeness (that is the proportion of the fuel that actually burned). Usually, burned area is derived from remote sensing data. Fuel loads and combustion completeness are not that easy to come by using remote sensing. They are either derived from default values for different land cover types (e.g. IPPC default values) or from biogeochemical models and remote sensing data (*1*). These two parameters therefore add substantial uncertainty to the emissions estimate. This approach is often called the indirect method for estimating biomass burned.

Estimating fuel consumption directly (without having to worry about fuel load and combustion completeness) is possible through measuring the heat released by the active fire. The more heat a fire generates, the higher is the combustion rate. The heat, or energy release rate, can be measured using infrared sensors (Figure 1).

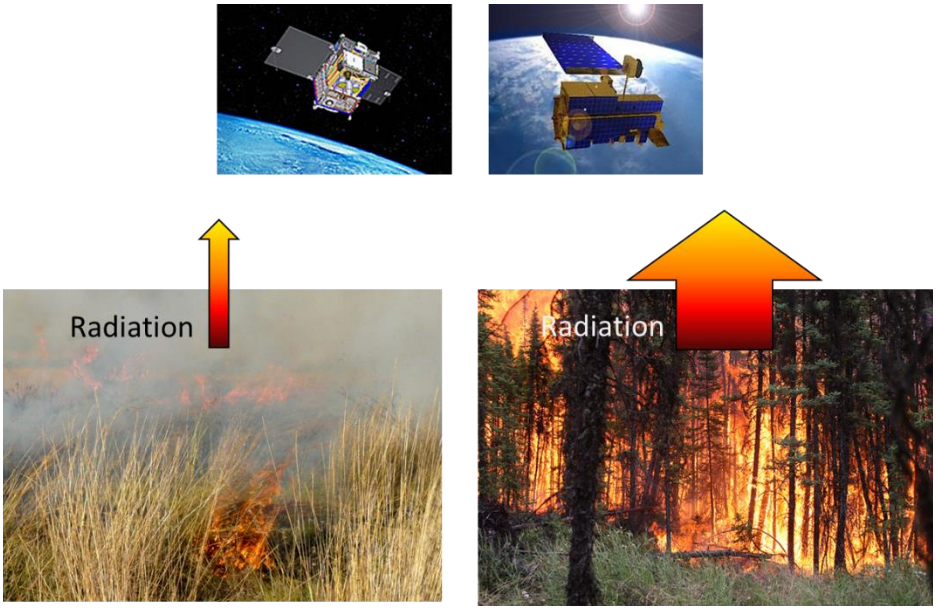

Figure 1 : Illustration of the concept for estimating fuel consumption from the heat release as observed by satellites: small fires consume little biomass and hence release little heat and little infrared radiation is observed, whereas a strong fire release a lot of heat and therefore a strong signal is observed by the satellite. The German BIRD satellite and the US American Terra satellite shown in the figure were the first to be able to quantify this heat release.

Measuring heat of burning fires using satellites has become possible with data from the MODIS sensors aboard the still operating Terra and Aqua satellites more than 15 years ago. Hence, the measurement of the fire radiative energy (FRE) released during burning offers an attractive way for the calculation of fuel consumed. It has been shown that FRE can be converted to fuel consumption using a scaling factor, which is constant within narrow bounds in time and for all locations (*4*). This is due to the very similar heat content of vegetation across ecosystems. In firemaps.net, an empirical correction factor is applied to that scaling factor to compensate for different loss mechanisms that the emitted radiation undergoes on the way from the fire to the satellite (*5*).

This approach has the great advantage that it permits near real time emission estimates and that it relies on measurement of physical properties directly related to combustion, while the "classic" indirect method depends on estimates of various factors influencing combustion, and is hence potentially more error-prone. Therefore, this relatively new method is used by the European operational service for monitoring trace gas emissions from fires on a global scale and for pollutant dispersion forecast (*6*).

However, only a limited number of such observations are available for each fire. The MODIS sensor onboard of the Aqua and Terra satellites provides up to four observations a day, but this number may be reduced through observational gaps and clouds. Therefore, a statistical modelling approach was developed for firemaps.net to derive hourly FRP estimates. The model uses burned area, weather observations and land cover information/fuel loadings as covariates to estimate hourly FRP (Figure 2).

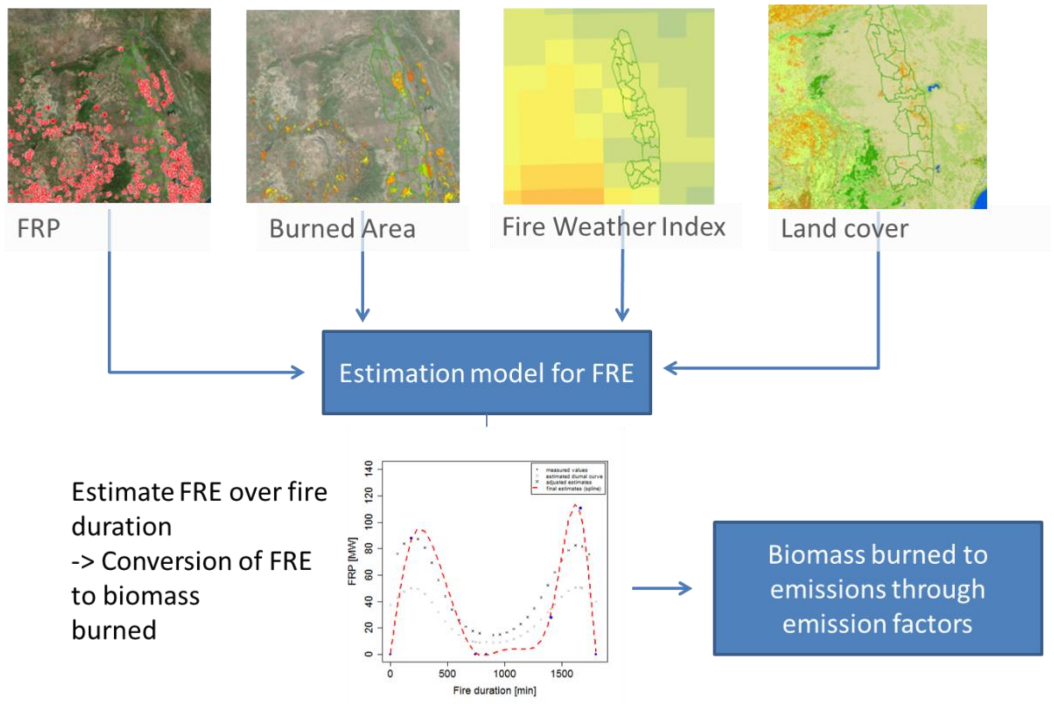

Figure 2: Schematic graph of the process for estimating fire emissions in the project. The model estimates hourly fire radiative power (FRP) and then derives biomass burned from FRP. Biomass burned is converted to emissions through applying standard emission factors for each trace gas.

Hourly FRP estimates are integrated to daily total fire radiative energy (FRE). Since FRE is proportional to the total biomass burned it can be converted to a daily estimate of biomass burned (*4*).

During the combustion process biomass undergoes a series of chemical reactions, and most of the carbon contained in the plant tissue is oxidized to carbon dioxide, but part of it will be released as carbon monoxide, methane or as one of many other organic compounds, or be blown into the atmosphere in smoke particles.

The amount of these gases or particulates released per kilogram biomass burned is more or less constant within a biome, and hence emissions can be estimated from the amount of biomass combusted.

Therefore, in firemaps.net, biomass burned derived from satellite measurements is converted to emissions for different trace gases through the application of standard emission factors (Figure 2).

An example of the working of the model is demonstrated for a fire in Comoé National Park, Côte d'Ivoire, which burned in December 2016. A MODIS satellite image of the burned area and the fire at the first day of detection is shown in Figure 3. The FRE calculation for this fire is based on all MODIS active fire detections over the fire throughout the fire lifetime. The fire emissions algorithm calculates graphs for estimated hourly fuel consumption rate (Figure 4) and for daily estimated burned biomass (Figure 5) for every fire that has more than three detections.

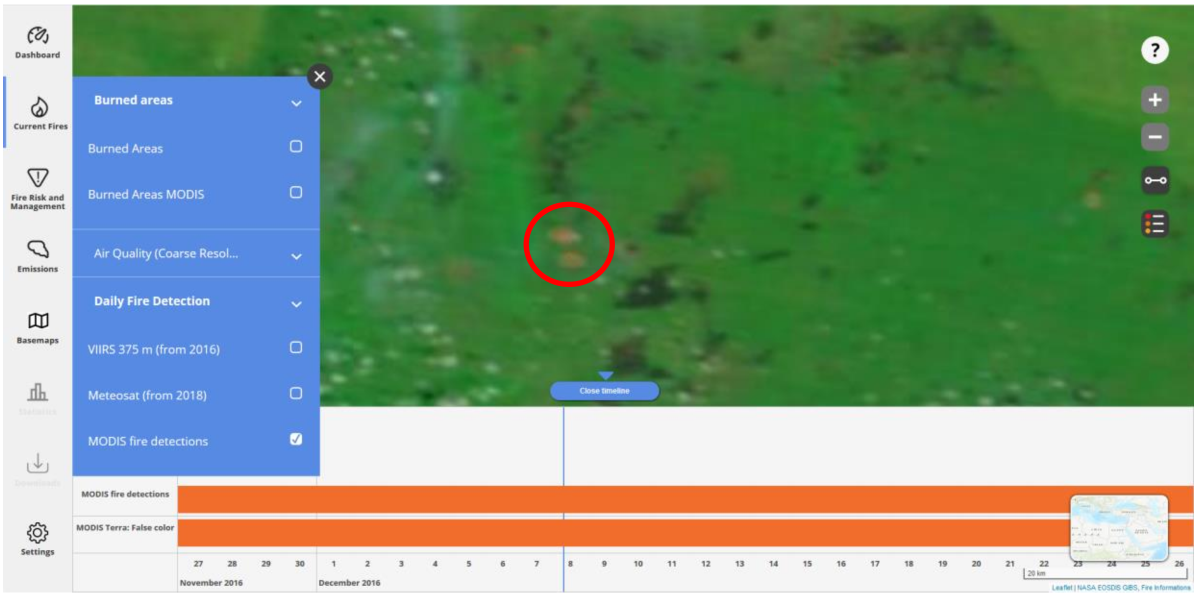

Figure 3: firemaps.net user interface with MODIS aqua image taken on 8th December, 2016 of the area quantitatively described in Figure 4 and Figure 5 which is marked by the red circle. Orange areas inside the circle are highly active flaming areas.

Since MODIS data are available back to 2003, a long time series can be established in an automated manner for any area on the basis of this approach. Such a time series can help understanding the recent fire history in an area, and provides a baseline against which fire management activities can be assessed. This is particularly important due to the high inter-annual variability found in many areas. Observations made only for two or three years are therefore not sufficient to define a baseline which is necessary to judge the impact of management activities on fire emissions, e.g. on the scale of an entire protected area.

Estimating emissions from fires is a highly complex task, and there are many uncertainties involved in this process. Hence, it is important to understand that the emission estimates have an attached uncertainty range, and only a change in emissions that is above or below that uncertainty range can be considered a real and measurable change. At firemaps.net we have therefore invested considerable effort to constrain these uncertainties. A detailed discussion is provided in the annex of this whitepaper.

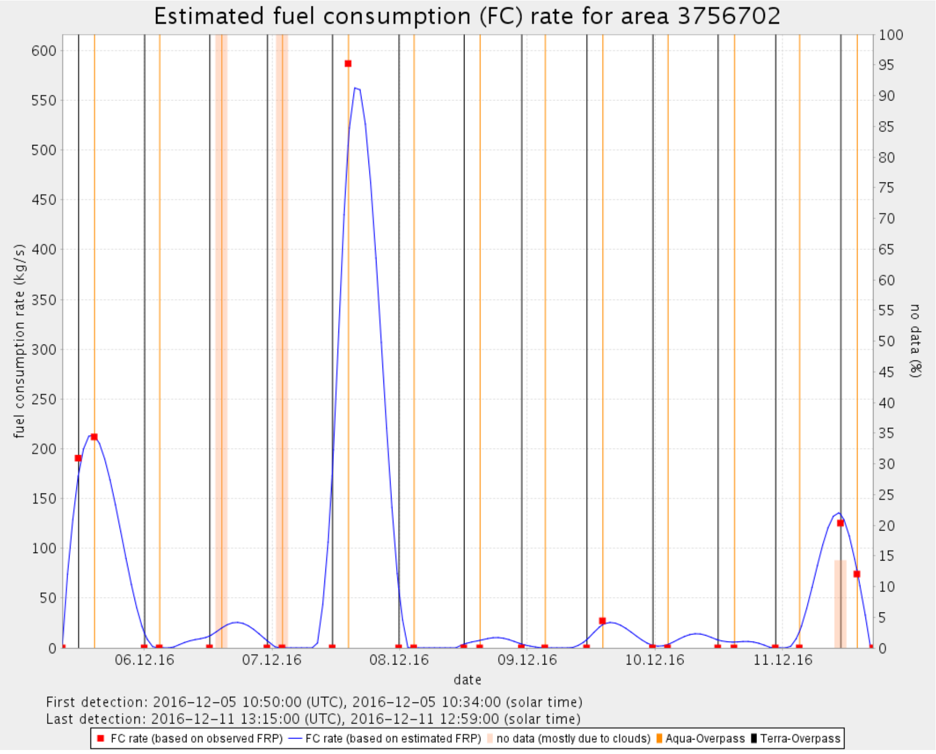

Figure 4: Estimated fuel consumption rate (in kg/s, left vertical axis) for the fire in Figure 3 from first to last MODIS active fire detection. Each red dot corresponds to a MODIS overpass and indicates the total FRP measured over the fire, which is converted to fuel consumption. The Blue lines are interpolated fuel consumption rates. The vertical thin bars indicate overpasses of the MODIS satellite (orange: Aqua, black: Terra), the fat light orange bars indicate percentage of no data, e.g. due to cloud cover (in %, right vertical axis).

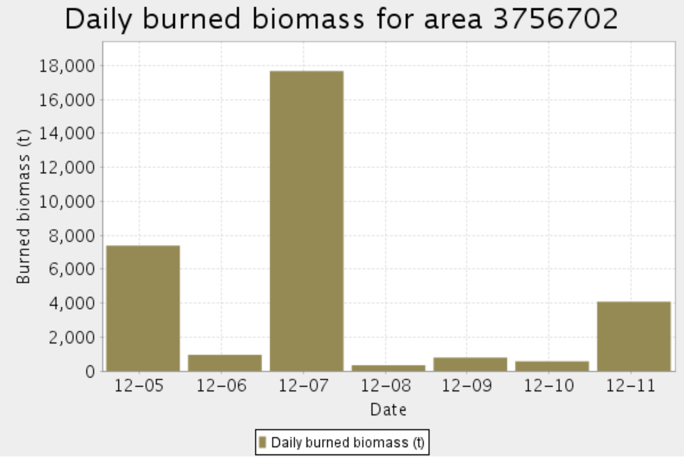

Figure 5: Estimated daily biomass burned based on the modelled fuel consumption rates in the previous figure.

3.2 Comparison to field data

Field data are important to verify the models of fuel consumption and fire behavior. We therefore strive to assess quality of our products in the field either in cooperation with project partners our through own measurements. Estimates of our fuel consumption algorithm have been compared to field data in project areas in Brazil, Côte d'Ivoire and South Africa. Results show that the firemaps.net estimate is similar to field observations and generally field and remote sensing based values are within the uncertainty range of each measurement.

Figure 6: An experimental fire in Comoé National Park, Côte d'Ivoire is observed by radiometers mounted on six meter poles to measure the heat release of the fire in a similar manner as a satellite does.

Comparison to a global dataset, the Global Fire Emissions Database (GFED(*1*)) also shows good general agreement with the firemaps.net estimate. GFED as a global dataset, however, does not offer the spatial resolution firemaps.net offers.

Figure 7 : fuel load and fuel consumption are assessed in the filed in Comoé National Park, Côte d'Ivoire

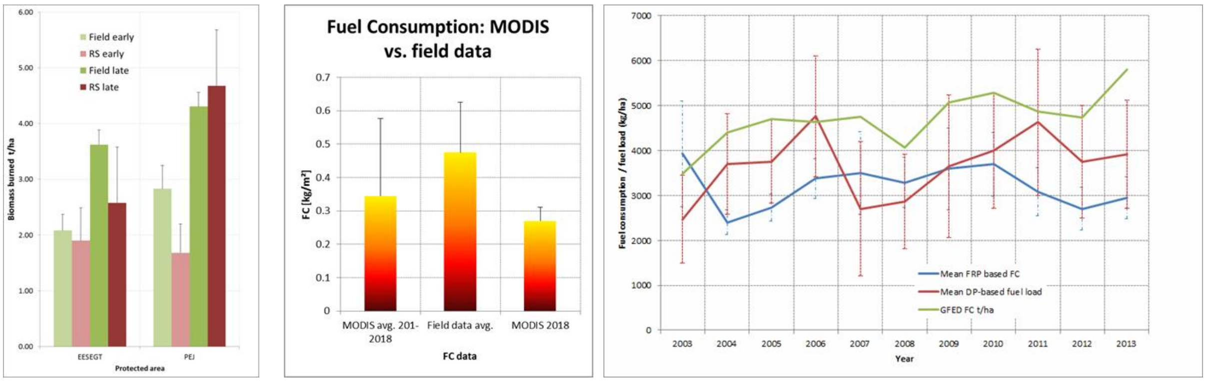

Figure 8 : Comparison of firemaps.net fuel consumption estimates to field data: left: comparison to results of early and late season burns in a savanna area in Central Brazil[1], center: comparison of eight year of MODIS derived FC average and field data gathered in the same fires season in Comoé National park, Côte d'Ivoire, and right: comparison of field averages of permanent experimental burn plots (red line) in Kruger National Park, South Africa[2] to firemaps.net MODIS derived fuel consumption estimates (blue lines) and to the Global Fire Emissions Database (green line).

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[1] Field data provided by Isabel Schmidt et al., University of Brasilia within the Cerrada Jalapao Project

[2] Field data provided by Navashni Govender, Scientific Services at South African National Parks within Research Agreement RUECKG 1112 APPS4GMES

4 PRACTICAL APPLICATIONS

Reduction of emissions can have positive impacts on the global climate and on regional air quality. Reducing emissions is therefore often a part of fire management strategies in frequently burning landscapes such as savannas. To make practical use of the emissions monitoring and baseline information in firemaps.net, this information has to be linked to fire management objectives and strategies. Here we show how such a linkage can be implemented in firemaps.net, taking also into consideration the possibility of acquiring financial support for improved fire management through green climate funding. We start with a note on carbon and fire in savanna type ecosystems.

4.1 Some notes on carbon and fire in savannas

Savannas are characterized by a distinct dry and wet season. Woody and herbaceous plants (dominated by grasses) coexist, and the seasonally dry grass layer provides fuel for large and frequent fires. Hence, fire is a major agent in most savanna landscapes that are not impacted by conversion to another land use. Carbon flux from fires can be in the order of net primary productivity. Aside from the direct emissions, fires have an indirect effect on net ecosystem productivity e.g. through effects on productivity or mortality of woody vegetation. Despite the large fire fluxes, most savanna sites act as a carbon sink (again without land use change).

The interaction of fire, woody cover and the carbon stocked in woody vegetation and in soils in savannas is a complex one, and is influenced by fire frequency, intensity and seasonality on the one side, and specific site conditions such as soils, water availability, and proximity to seed trees, and interaction with herbivores on the other. This makes direct measurements allowing quantification of substantial stock changes over short time periods difficult.

Assessing direct fire fluxes, in turn, is less challenging, although uncertainty is still large. However, the direct fire carbon flux may in essence be carbon neutral, since the carbon lost in grass-dominated fires is quickly replaced by regrowth.

The fire flux of those non-CO_2 greenhouse gases that are stronger greenhouse gases than $CO_{2,}$ does have a direct effect on global warming. These greenhouse gases are methane (CH_4) and Nitrous Oxide (N_2O). Carbon monoxide (CO) emitted by burning is not a greenhouse gas itself, but will undergo chemical reactions in the atmosphere that produce ozone, a potent greenhouse gas. These effects are measured in Global Warming Potentials which are calculated as CO_2 equivalents. For instance, one kg of Methane released has (over the next 100 years) the same global warming effect as 28 kg of CO_2, and one kilogram of nitrous oxide has the same effect as 298 kg of CO_2. Thus, even if emitted quantities are much lower than CO_2, the effect is still important.

CO_2, in turn, can be assumed neutral in respect to global warming, since most of the burned biomass is from grasses which are replaced by regrowth in the wet season. If grasses would not be burned, CO_2 would hence also be released during decomposition of the dead organic matter (dead grasses and litter).

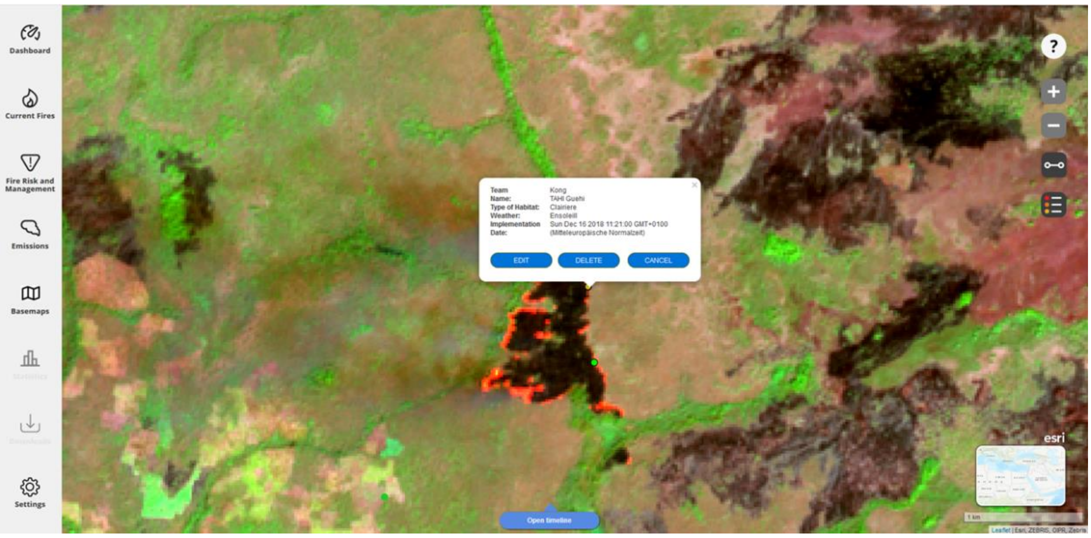
4.2 Shifting of burning patterns

A recent study estimated that a large potential exists for reducing emissions of Non-CO_2 GHG's in savannas through shifting seasonal burning patterns from late dry season to early season fires (*7*).

The study owns to the experience of the West Arnhem Land Fire Abatement (WALFA) project in Northern Australia, where emissions of Non-CO_2 GHG was reduced by 37% mainly through shifting burning patterns from late to early season fires (*8*). Most early season fires consume less fuel and emit less greenhouse gases than the usually more intense late season fires. In the WALFA project, a focus was given to reviving traditional burning practices which have been suppressed by colonial rule.

The firemaps.net technology can be used to both assess the feasibility of such a reduction for a project area through analysis of emission baseline data as well as for monitoring implementation success.

Implementation of management fires can be planned, documented and success tracked against an underlying management plan using firemaps.net technology (Figure 9).



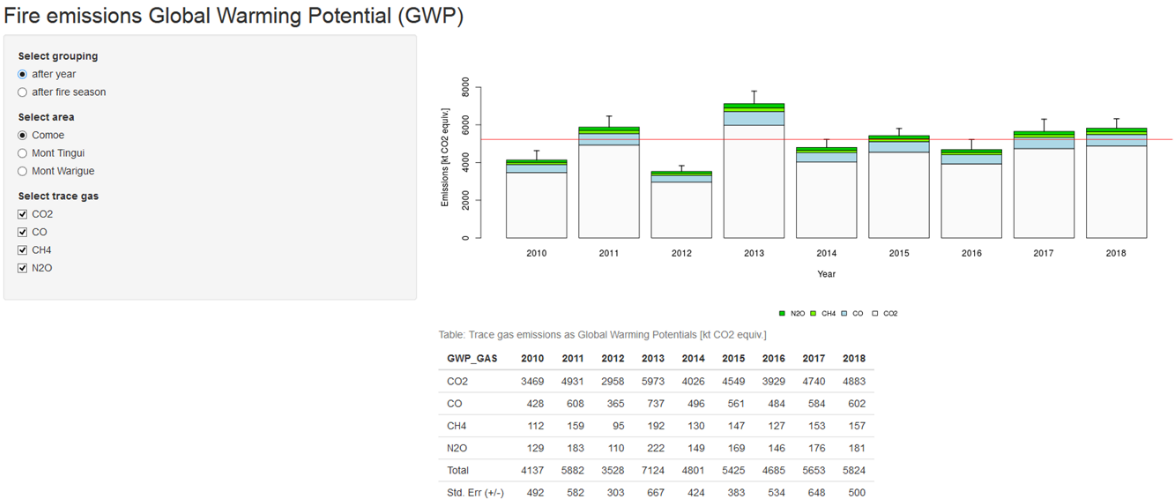
Team Kong
Name: TAHI Guehi
Type of Habitat: Clairiere
Weather: Ensoleill
Implementation Date: Sun Dec 16 2018 11:21:00 GMT+0100 (Mitteleuropäische Normalzeit)

Figure 9: Documentation of management fires with firemaps.net in Comoé National Park, Côte d'Ivoire: The ignitions are documented in firemaps.net using an online tool. Management fires can then be evaluated against the management objectives specified in a management plan which is also stored in firemaps.net.

4.3 Assessing reduction of direct emissions of Non-CO_2 GHGs

To estimate if a significant reduction of direct emissions of Non-CO_2 GHGs could be effective, the average seasonal Non-CO_2 emissions of the last fire seasons should be calculated as a baseline in firemaps.net (Figure 10). Based on the average fire emissions per unit area (also available in firemaps.net), the amount of reduction in burned area can be estimated. Also, late and early season fuel consumption can be assessed to calculate the potential emission reduction in shifting from late to early season burning. Furthermore, the uncertainty of measurement needs to be considered by implementing a margin (about 15

%) dependant on the measurement error. To estimate feasibility of such an effort in improving fire management, a fire management plan for the project area needs to be elaborated. Firemaps.net can also support this activity by providing relevant base data on the fire regime in different land cover/land-use units (Figure 11).


Fire emissions Global Warming Potential (GWP)

Select grouping
● after year
○ after fire season

Select area
● Comoe
○ Mont Tingui
○ Mont Warigue

Select trace gas
☑ CO2
☑ CO
☑ CH4
☑ N2O

Table: Trace gas emissions as Global Warming Potentials [kt CO2 equiv.]

GWP_GAS	2010	2011	2012	2013	2014	2015	2016	2017	2018
CO2	3469	4931	2958	5973	4026	4549	3929	4740	4883
CO	428	608	365	737	496	561	484	584	602
CH4	112	159	95	192	130	147	127	153	157
N2O	129	183	110	222	149	169	146	176	181
Total	4137	5882	3528	7124	4801	5425	4685	5653	5824
Std. Err (+/-)	492	582	303	667	424	383	534	648	500

Figure 10 : Timeline of greenhouse gas emissions in the firemaps.net statistics dashboard. The user can select different study areas, groupings and different greenhouse gas species.

Legend

Management ▲

High fire intensity treatment
🟥 Shurb savannah buffer around main road
Low intensity early season treatment
🟥 Tree savannah
🟧 Buffer around fire exclusion areas
Vulnerable areas - fire exclusion
🟦 Bas-fonds
🟦 Fleuve Comoe
🟩 Galerie forestiere
🟩 Ilot forestier
No specific treatment
⬜ No specific treatment

Figure 11 Management map for prescribed fires in the Comoé National Park, Côte d'Ivoire.

Using management fires, the late season dominated fire regime in a number of protected areas in Brazil could be shifted towards an early season fire regime. Emission patterns calculated with the firemaps.net technology shifted accordingly (**Figure 12**).

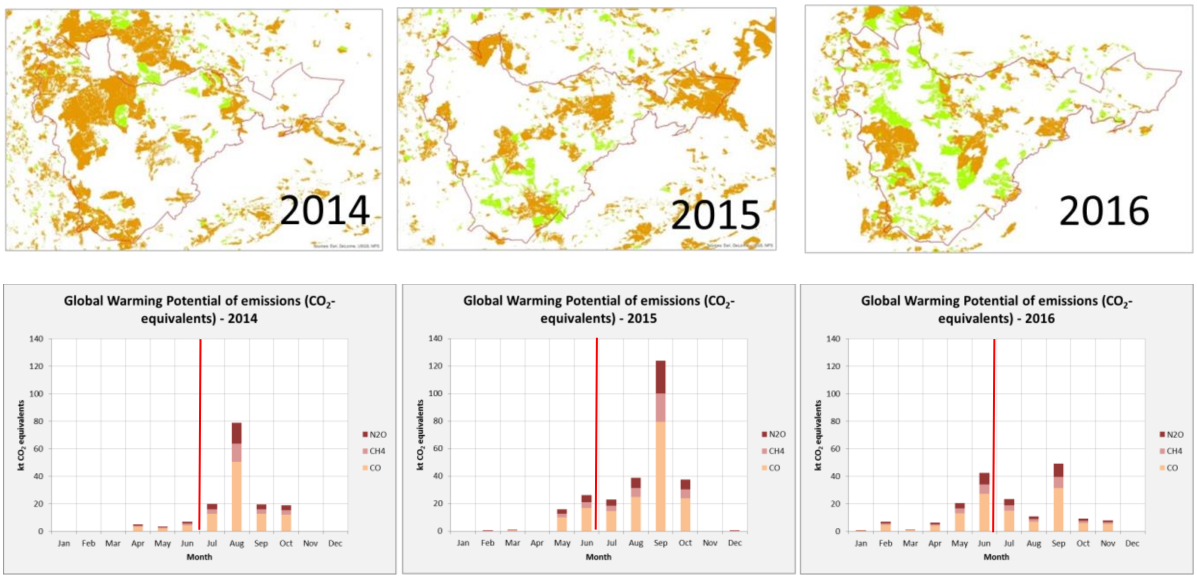


Figure 12 Time series of fire seasonality (above) and monthly non-CO_2 greenhouse gas emissions (below) for Estacion Ecologica de Serra Geral do Tocantins, Central Brazil. Green patches in the maps indicate early season fires, brown patches late season fires. The red line in the bar charts indicates the date cutoff between early (before 1st July and late (after 1st July).

4.4 Increase of carbon stocks

A more benign fire regime would probably shift the competitive advantage of trees over grasses near gallery forests in savanna landscapes, and also reduce soil erosion. Thus, improved fire management practices can also aim at reducing the impact of fire on vulnerable areas.

The objective of these controlled burns is to remove fuels around the vulnerable areas using controlled, early season fires of low to moderate intensity in order to exclude more intense late season fires. There are functions on modelling fire intensity available in firemaps.net which are designed to help managers find the “sweet spot” where fires are intense enough to effectively remove the fuel but not as intense as to damage vulnerable areas. The functionality on modelling fire intensity will be described in more detail in a forthcoming white paper.

4.5 Funding of improved fire management

Understanding fire emissions in a project area is the key to assess the potential for reduction. To effectively implement a better fire management funding is needed both for the management activities and for monitoring reporting and verification systems and other activities like communication and participation of all stakeholders.

One of the main instruments for climate financing within the Paris agreement on Climate Change is the Green Climate Fund (GCF)[3], which was set up by the 194 countries who are parties to the United Nations Framework Convention on Climate Change (UNFCCC) in 2010, as part of the Convention’s financial mechanism.

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[3] https://www.greenclimate.fund)

The fund works through National Designated Authorities/Focal Points (often the Ministries responsible for Environment) and GCF Accredited Entities.

These entities can submit concept notes and proposals under the Simplified Approval Process (SAP) to request funding for climate mitigation and/or adaptation projects that meet the funding criteria [4]. Assistance in preparing project proposals is provided through the GCF.

A proposal for improving fire management and enhancing biodiversity could include both components of mitigation and adaptation. Mitigation means the reduction of greenhouse gas emissions from fires and/or the increase in carbon stocks e.g. due to a less severe fire regime. Adaptation means that adaptation of management to climate change – e.g. increased length of drought periods - is support by a financing mechanism.

Mitigation can encompass a number of management activities that support reduction of GHG emissions from fires, such as protecting vulnerable areas from late season fires and shifting burning patterns to early season burning including the application of patch or mosaic burns.

As shown in the previous sections, firemaps.net can support assessment of feasibility for such a funding proposal, estimating potential of emission reduction, as well as monitoring and implementation of an emission reduction project. Through a public or restricted web interface, firemaps.net can also provide a means to communicate project success to selected stakeholders and/or the wider public.

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[4] The funding criteria are: 1. the funding request is up to 10 Million US-$, 2. the project must be scalable to larger areas and 3. the project must have no or negligible environmental impact.

CONTACT INFORMATION

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5 ANNEX

5.1 Data

We use active fire detections from the MODIS instruments provided through NASA and USGS. The data consist of a list of pixel coordinates with ancillary information such as FRP and a fire mask indicating the location of active fire detections, clouds, clear land and water. The fire mask is used to identify cloudy or partially obscured observations.

Burned areas are either extracted form a long term dataset derived from 500 m resolution MODIS data (*9*), or can be mapped at high resolution from Landsat and Sentinel 2 data.

Land cover, which is an input to our FRP estimation model, is extracted from the global MODIS land cover dataset available through NASA and USGS (*10*).

To estimate the Canadian Fire Weather Index, (FWI, another input for the FRP estimation model) we use a global dataset (*11*) or weather data retrieved from a commercial provider.

The datasets used are summarized in table 1.

Table 1: Datasets used in firemaps.net

Dataset	Purpose	Source	Remarks
MODIS MCD 64 burned area	Burned area and most probable date of burning	NASA	500 m resolution. (*9*)
MODIS MOD/MYD 14 active fires	Active fire detections and fire radiative power	NASA	1 km resolution at Nadir (*12*)
Landsat 8 satellite images	Burned area mapping 2016/2017	USGS	
Sentinel 2 satellite images	Burned area mapping 2016/2017	ESA	
Darksky.net Weather data	Wind, temperature and humidity	darksky.net API	
Global fire weather database	Fire weather data	NASA	(*11*)
Global precipitation data	Rainfall data 2016/2017	Downloaded from NASA	

5.2 Uncertainty in estimating fuel consumption

Like any measurement and any model, our estimates of fuel consumption and emissions have errors and uncertainties. It is crucial for a remote sensing product to provide a measure of uncertainty of the observed quantities. Without an estimate of uncertainty, any quantitative analysis will be of limited practical value. We have therefore put a lot of effort into describing and reducing the uncertainties of our approach. In the following, the main sources of uncertainties of our estimates of biomass burned are enumerated:

- Measurement precision of FRP in MODIS: this error depends mainly on the position of the fire front within a MODIS pixel. This uncertainty has been estimated to be up to 26% of the true value for single MODIS pixels, while it is lower for larger clusters (and hence less important if FRP is aggregated over space and time)(*13*).
- Error of omission (causing a low bias): Many fires will not be detected by MODIS, either because they are small and burn with less energy than the MODIS sensor can detect, or because they are short-lived and burn only between MODIS overpasses, or because the fire is obscured by clouds. Therefore, a varying percentage of burned areas do not have corresponding fire detections. We corrected for this by assigning these areas the monthly average fuel consumption per hectare of the month in which the fire burned. Also, for burned areas with fire detections, FRP may be underestimated. From previous work we can estimate this bias to be about 20% (*14*). This effect is corrected by an empirical correction factor (*5*).
- Error of commission (would cause a high bias): these are false alarms, i.e. erroneous fire detections. The false alarm rate of MODIS is very low, in most cases it is justifiable to neglect this error.
- Conversion of FRP to biomass burned: an error of +/- 5% for this conversion based on measurements over a range of fuels in laboratory conditions is assumed (*4*). Underestimation of FRP from satellites is corrected by an empirical correction factor (*5*).
- Estimation of FRP when no observations are available (approximation of the diurnal cycle of FRP): temporal undersampling of FRP is probably one of the largest sources of uncertainty, leading to a low precision of estimates. Our modelling approach tries to minimize this error.

Addressing uncertainty of emission estimates

Uncertainty is a key parameter when judging the effect on the carbon cycle and emissions through a change in the management system such as the shift from late season fire to early season fires through the application of controlled burns. Total uncertainty is affected by the uncertainty in the estimate of biomass burned and by the uncertainty in the emission factors (g GHG released per kilogram fuel consumed). When calculating Global Warming Potentials to express all emissions in units of CO_2 equivalents, this calculation has an additional uncertainty attached which influences the estimate of GWP's.

Any measurement has two components of uncertainty: bias and precision, which together define the overall accuracy of a measurement. Bias defines a systematic error, e.g. a low bias describes the tendency of a measurement to underestimate the true value. Precision describes variability of measurements and is usually described by the standard deviation of the mean from the true value. The concepts are illustrated in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

The precision of the biomass consumption estimate is assessed using a statistical model called "jackknife resampling". The precisions given in estimates of emission factors are based on the range found in literature studies for savanna landscapes, and the precision in conversion to global warming potential are based on the latest IPCC assessments. In the charts in firemaps.net, all error bars indicate one standard error. This means that we expect a 68% probability that the true value will be between these error bars.

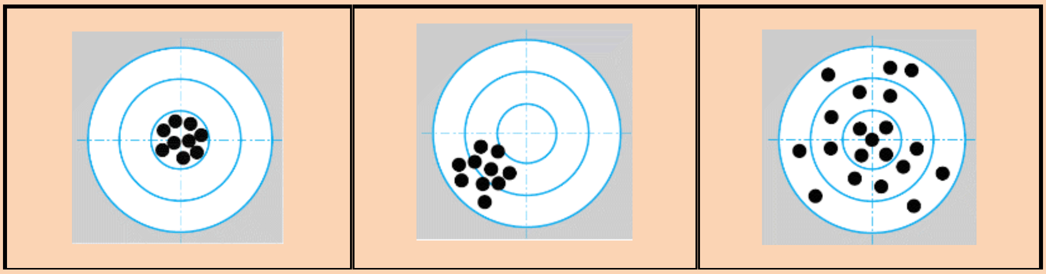

Figure 13: Illustration of the concept of bias and precision: the true value is in the center of the dart screen. The left panel indicates a measurement with high precision and low bias – the optimal case. The middle panel indicates a measurement with high precision but is also highly biased, while the right panel indicates a measurement with low precision which is rather unbiased.

While the precision for estimating biomass burned and emissions for a single fire is rather low (jackknife resampling often indicates a standard error of >50% of the mean), the precision for an entire protected area is substantially higher since over- and underestimations tend to cancel out due to the large sample of burned areas.

To constrain the unsystematic errors due to observation gaps and measurement error, the delete-1 jackknife method, a statistical resampling method, was used. It is based on omitting, for each subsample (in our case each fire), one observation at a time (i.e. one MODIS FRP measurement). In our approach we thus derive an estimate of FRE (the total energy release) by purposefully omitting MODIS FRP observations, and recalculating the FRE value. We do this for each fire as many times as we have observations over the fire. The jackknife mean is then the mean of all of these calculations, and the jackknife variance the variance over all observations for this fire. To estimate the uncertainty in the emissions estimates, the jackknife mean and the jackknife variances for all fires are summed up. The jackknife standard deviation is then calculated as the square root of the variances. The ratio of the Jackknife standard deviation to the total biomass consumed is the relative standard error which is used for error propagation calculations.

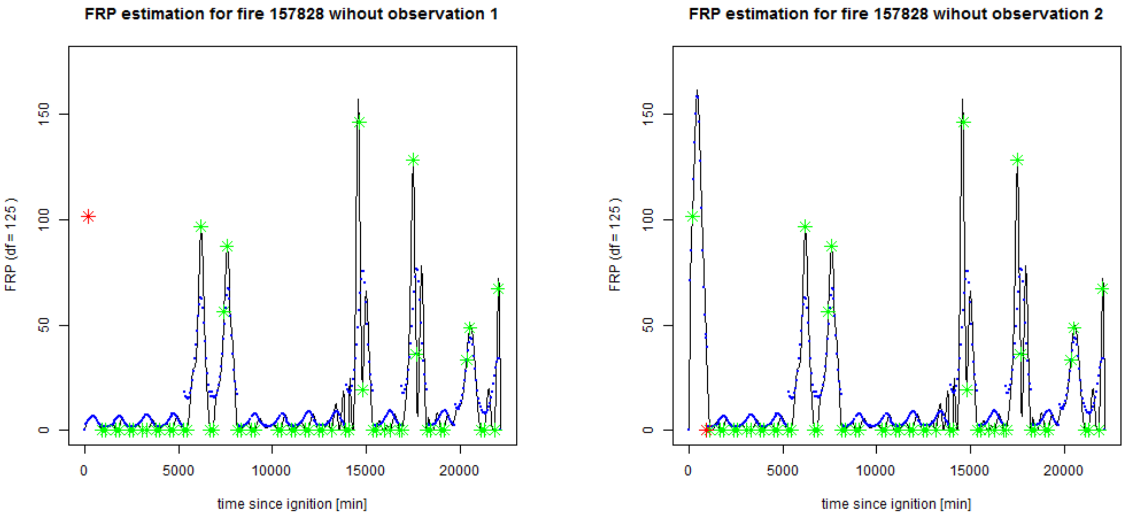

Figure 14: Illustration of the delete-1 jackknife method: to obtain an estimate of the uncertainty caused through missing observations and FRP retrieval error, each FRP observation over a fire with more than three observations is omitted and replaced by modelled values. Left panel: hourly FRP estimation with omission of the first observation (red *), right panel: hourly FRP estimates with omission of the second observation (red *), Green * are observations used in the estimate.

5.3 Uncertainty in emission factors and Global Warming Potentials (GWP)

We use emission factors to convert biomass burned to mass of greenhouse gas emitted based on emission factors from the peer-reviewed literature (*15, 16*). These papers contain a literature review on emission factors compiled from a number of studies, and a range indication of natural variability in the case of the Akagi (*15*) database, and a standard deviation in the case of N_2O from the Andreae and Merlet (*16*) database.

We use both the range and the standard deviation given in these papers as estimates of the standard error, which may of course lead to a substantial overestimation of errors.

Having site specific emission factors obtained through experimental fires may considerably reduce uncertainty due to emission factors.

Likewise, we use the Global Warming Potentials and their standard errors given by IPCC in their 4th Assessment report to estimate GWP uncertainty.

Uncertainty of emissions and GWPs for the study areas are then derived using the standard approach on error propagation[5].

Table 2: Emission factors and Global Warming Potentials (in CO_2 equivalents) used in firemaps.net for the savanna biome. GWPs are from the IPCC 4th Assessment report (*17*).

Species	Ef (g/kg)	Range (g/kg)	Source	GWP (dimensionless)	GWP error
CO_2	1686	38	Akagi et al, 2011	1	-
CO	63	17	Akagi et al, 2011	3.3	0.8
CH_4	1.94	0.85	Akagi et al, 2011	28	5.6
N_2O	0.21	0.1	Andrae and Merlet, 2001	298	n.a.

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[5] An „easy" mathematical explanation of error propagation is e.g. found here: http://ipl.physics.harvard.edu/wp-uploads/2013/03/PS3_Error_Propagation_sp13.pdf

6 LITERATURE

1. G. R. van der Werf *et al.*, Global fire emissions estimates during 1997–2016. *Earth System Science Data* **9**, 697-720 (2017).
2. V. Huijnen *et al.*, Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997. *Scientific Reports* **6**, 26886 (2016).
3. S. N. Koplitz *et al.*, Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure. *Environmental Research Letters* **11**, 094023 (2016).
4. M. J. Wooster, G. Roberts, G. L. W. Perry, Y. J. Kaufman, Retrieval of biomass combustion rates and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release. *Journal of Geophysical Research* **110**, (2005).
5. N. Andela *et al.*, Biomass burning fuel consumption dynamics in the tropics and subtropics assessed from satellite. *Biogeosciences* **13**, 3717-3734 (2016).
6. J. W. Kaiser *et al.*, Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power. *Biogeosciences* **9**, 527-554 (2012).
7. G. J. Lipsett-Moore, N. H. Wolff, E. T. Game, Emissions mitigation opportunities for savanna countries from early dry season fire management. *Nature communications* **9**, 2247 (2018).
8. J. Russell-Smith *et al.*, Managing fire regimes in north Australian savannas: applying Aboriginal approaches to contemporary global problems. *Frontiers in Ecology and the Environment* **11**, e55-e63 (2013).
9. L. Giglio, J. T. Randerson, G. R. van der Werf, Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). *Journal of Geophysical Research: Biogeosciences* **118**, 317-328 (2013).
10. M. A. Friedl *et al.*, MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote Sensing of Environment* **114**, 168-182 (2010).
11. R. D. Field *et al.*, Development of a global fire weather database for 1980–2012. *Natural Hazards and Earth System Sciences Discussions* **2**, 6555-6597 (2014).
12. L. Giglio, W. Schroeder, C. O. Justice, The collection 6 MODIS active fire detection algorithm and fire products. *Remote Sensing of Environment* **178**, 31-41 (2016).
13. P. H. Freeborn, M. J. Wooster, D. P. Roy, M. A. Cochrane, Quantification of MODIS fire radiative power (FRP) measurement uncertainty for use in satellite-based active fire characterization and biomass burning estimation. *Geophysical Research Letters*, 2013GL059086 (2014).
14. G. Ruecker *et al.*, paper presented at the The 5th International Wildfire Conference, Sun City, South Africa, 9-13 May 2011 2011.
15. S. K. Akagi *et al.*, Emission factors for open and domestic biomass burning for use in atmospheric models. *Atmospheric Chemistry and Physics* **11**, 4039-4072 (2011).
16. M. O. Andreae, P. Merlet, Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles* **15**, 955-966 (2001).

17. G. Myhre *et al.*, in *Climate Change 2013: The Physical Basis. Contribution of Working Group I to the Fifth Assessment Report of the Ontergovernmental Panel on Climate Change,* T. F. Stocker *et al.*, Eds. (Available from www.climatechange2013.org and www.ipcc.ch, 2013).

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