SUPPLEMENTARY MATERIAL

Performance of low-cost monitors to assess household air pollution

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- **Figure S4**: Time-series showing the carbon monoxide (CO) levels measured by the benchmark monitor (Q-Trak) and the three low-cost units (EL-USB-CO) and temperature in the experiment.
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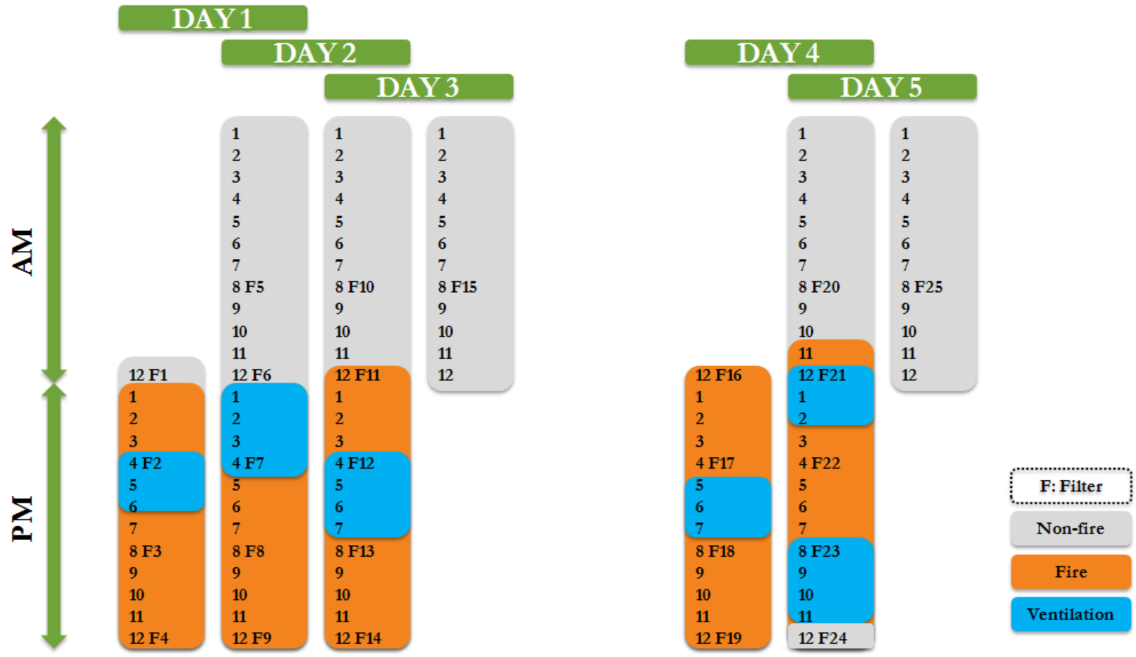
- **Table S1**: Summary table of characteristics of the used and excluded air quality devices.

- **Table S2**: Descriptive table of all the parameters measured by the benchmark monitors used in the validation study, split by fire and room ventilation conditions.
- **Table S3**: Adjusted R^2 (in percentage) for the fitted models and partial contribution to R^2 of each term in the model.
- Expanded version of the Methods section.
- R script to read the raw output files of the main devices used in the study.

Figure S1 Diagram of the time course of the wood-combustion experiment.



F= a change of the Teflon filter from the BGI pump was done.

The experiment was divided conveniently into three consecutive days and 2 separate consecutive days, having in total 5 non-consecutive days. Almost all days fire was set at 12-1pm (in orange). Window was only opened during fire hours (in blue). A total of 25 gravimetric filters were obtained (F1-F25).

Table S1 Summary table of characteristics of the used and excluded air quality devices.

Device [software used, if applicable]	Model (university/ company)	Detection method of PM / CO	Measure(s)	PM / CO Range [1]	Battery life [1]	Max. Operating T (ºC) [1]	Cost per unit (US Dollar)	Used?	Exclusion reason(s)
Particle and Temperature sensor (PATS+)	PATS+ (Berkeley Air Monitoring Group)	light-scattering (Sharp GP sensor) / electrochemical (COA4 Alphasense sensor)	$PM_{2.5}$, CO, T, RH, movement	10 $\mu g/m^3$ to 50 mg/m^3 ($PM_{2.5}$) / 0 to 500 ppm (CO)	> 80 hours	+50	~ 550 (depending on quantity and the optional inclusion of the CO sensor)	No	Not available for retail until September 2016
Ultrasonic Personal Aerosol Sampler (UPAS)	UPAS v2.0 (Colorado State University and Access Sensor Technologies)	ultrasonic piezoelectric pump [2]	$PM_{2.5}$, T, RH, movement, UV light	25 to 800 $\mu g/m^3$	23-45 hours [2]	+85 (BME280 sensor from Bosch Sensortec)	~ 150 [2]	No	Filter-based
Dylos	Model DC1700 (Dylos Corporation)	light-scattering (with fan)	$PM_{2.5}$, PM_{10}	0.5 to 1 000 $\mu g/m^3$	6 hours	Not reported	425	No	Short battery life and already validated in indoor environments
DustTrak DRX [TrakPro v4.1.0.]	DRX Aerosol Monitor 8534, hand-held (TSI Inc.)	light-scattering and gravimetric [3]	PM_1, $PM_{2.5}$, PM_4, PM_{10}	0.001 to 150 mg/m^3	6 hours	+50	~ 8,000	Yes	-

BGI/Mesa Labs pump (discontinued)	BGI4004-Personal IAQ Monitor (4-6 lpm) (BGI/Mesa Labs)	gravimetric	$PM_{2.5}$, absorbance[4]	Non applicable (although commonly filters accumulate 10 to 25 µg of mass)	24 hours	+50	> 1,000	Yes	-
SKC pump	Model Universal PCXR8 (0,005 to 5 lpm) (SKC Inc.)	gravimetric	$PM_{2.5}$, absorbance[4]	Non applicable (although commonly filters accumulate 10 to 25 µg of mass)	12 hours (with extended times with intermittent sampling)	+40	> 1,000	Yes	-
TZOA-R	TZOA Research Devices (RD02) (MyTZOA)	light-scattering (with fan)	PM_1, $PM_{2.5}$, PM_{10}, T, RH	Not reported	60 days	+40	400	Yes	-
HAPEX [HAPEX Nano Launcher v2]	HAPEX Nano, firmware version 1.0 (Climate Solutions Consulting)	light-scattering (without fan)	$PM_{2.5}$	5 µg/m^3 to 150 mg/m^3	2 years	Not reported	95	Yes	-
Atmotube	Atmotube	Not a selective	CO, VOCs,	100 to 1 000	1 month	+45 (for best	89 (retail)	No	Not available at

	(NotAnotherOne with technology from Arrow Electronics)	sensor for CO (estimated indirectly by tVOCs sensor highly sensitive to CO)	T, RH	ppb (tVOCs)		accuracy: +30)			the time of the study and low robustness to long term meteorological extremes
Foobot	Foobot (Airboxlab with technology from TechCrunch)	light-scattering (Sharp GP sensor) / metal oxide	$PM_{2.5}$, CO and CO_2 indirectly, VOCs, T, RH	0 to 1.6 mg/m^3 ($PM_{2.5}$)	plugged	+60	190	No	Lack of internal battery (i.e. electricity dependant) and CO detection range too low (from 0.1 to 1ppm)
NODE+	NODE+ Sensor Platform NK-02B with NODE+OXA CO sensor (Variable Inc.)	electrochemical	CO	0 to 1 000 ppm	54 days (in standby time)	+50	149 platform (+75 sensor)	No	Difficulties to transmit the data wirelessly through Bluetooth to an iOS and Android smart devices (tested by authors) and impossibility to

									upload the data to a computer
Dräger	Dräger Pac 7000 (Drägerwerk AG)	electrochemical	CO	0 to 1 999 ppm	24 hours	+50	487 (+ 147 USB cable)	No	Short battery life
Aeroqual	Aeroqual s500 (Aeroqual Ltd.)	electrochemical	CO	0 to 1 000 ppm	8 hours	+45	704 (only the sensor head)	No	Expensive and short battery life
CO-O3	Single Gas Personal Monitor, CO-Series 03 (RKI Instruments)	electrochemical	CO	0 to 500 ppm	125 days (replaceable)	+50	449 (+190 software + 267 USB cable)	No	Expensive
Indoor Air Pollution (IAP) Meter	IAP Meter 5000 series (Aprovecho Research Centre)	light-scattering and electrochemical	$PM_{2.5}$, CO T, RH	0 to 60 mg/m^3 ($PM_{2.5}$) / 0 to 1 000 ppm (CO)	3 to 30 days (depending on sample frequency mode)	Not reported	~ 2,500	No	Expensive
Q-Trak [TrakPro v4.1.0.1]	Indoor Air Quality Monitor 7575 with IAQ Probe Model 982	NDIR (CO2), electrochemical (CO)	CO_2, CO, T, RH	0 to 500 ppm	6 hours	+45	3,100	Yes	-
EL-USB-CO [EasyLog]	Lascar EL-USB-CO	electrochemical	CO	0 to 1 000 ppm	3 months (with specific settings and with a non-	+40	125	Yes	-

					rechargeable 1/2AA 3.6V battery)				

PM_1: particles less than 1 μm; $PM_{2.5}$: particles less than 2.5 μm; PM_4: particles less than 4 μm; PM_{10}: particles less than 10 μm; T: Temperature; RH: Relative Humidity;

CO_2: Carbon Dioxide; CO: Carbon Monoxide; NDIR: Non-Dispersive Infra-Red absorption; UV: Ultraviolet light; VOCs: Volatile Organic Compounds; tVOC: Total VOCs.

1. *According to operating manufacturer manuals or datasheets. Battery life varies according to the settings specified.*
2. Volckens, J. *et al.* Development and evaluation of an ultrasonic personal aerosol sampler. *Indoor Air* **27,** 409–416 (2017).
3. *Note that a pre-weighted filter can be loaded to the DustTrak DRX in order to avoid additional gravimetric pump and filter assembly.*
4. *Absorbance was also measured both in Spain and India, but data are not shown.*

Table S2 Descriptive table of all the parameters measured by the benchmark monitors used in the wood-combustion experiment, split by fire and room ventilation conditions.

	TOTAL				**NON-FIRE**				**FIRE, WINDOW OPENED**				**FIRE, WINDOW CLOSED**			
	n	min to max	mean ± SD	median	n	min to max	mean ± SD	median	n	min to max	mean ± SD	median	n	min to max	mean ± SD	median
UFP (pt/cm^3)	6270	0 to 586745.2	28575.8 ± 47263.4	16170.0	3006	0 to 212480.6	12706.8 ± 17108.3	16170.0	868	8570.0 to 156847.0	24545.3 ± 20341.7	18202.0	2396	4792 to 586745.2	49944.9± 67463.5	28085.5
PM_1(µg/m^3)	7031	6.0 to 588.0	42.7 ± 51.7	30.0	3672	6.0 to 588.0	26.8 ± 30.2	21.0	830	11 to 461	35.6 ± 32.6	24.0	2529	12.0 to 527.0	68.2 ± 68.7	46.0
$PM_{2.5}$ (µg/m^3), by BGI pump	25	5.1 to 94.8	34.5 ± 24.8	23.2	-	-	-	-	-	-	-	-	-	-	-	-
$PM_{2.5}$ (µg/m^3), by DustTrak DRX	7014	4.9 to 370.9	30.3 ± 32.9	21.5	3655	4.9 to 370.9	19.0± 18.8	14.8	830	8.9 to 311.7	27.5 ± 23.0	18.5	2529	8.7 to 332.9	47.6 ± 42.9	34.0
PM_{10} (µg/m^3)	7031	7.0 to 1990.0	69.3 ± 80.4	48.0	3672	7.0 to 682.0	41.9 ± 43.9	27.0	830	16.0 to 1990.0	41.9 ± 126.5	27.0	2529	17.0 to 808.0	105.2 ± 86.6	80.0
CO (ppm)	7135	0 to 9.8	0.7 ± 1.1	0.2	3748	0 to 4.4	0.2 ± 0.4	0.0	858	0.0 to 6.2	1.1 ± 1.2	0.7	2529	0.0 to 9.8	1.3 ± 1.4	0.9
BC (µg/m^3)	7176	0.1 to 8.3	1.6 ± 1.1	1.4	3783	0.06 to 8.1	1.3 ± 0.1	1.2	864	0.2 to 5.9	1.4 ± 0.8	1.3	2529	0.06 to 8.3	2.2 ± 1.2	1.9

T (ºC)	7261	19 to 55.5	29.4 ± 8.0	28.5	3864	19.5 to 43.5	23.6 ± 3.8	22.5	868	23.5 to 46.0	35.5 ± 5.5	35.5	2529	19.0 to 55.5	36.2 ± 6.5	34.5
RH (%)	7261	10 to 53.5	31.6 ± 9.6	32.0	3864	16.5 to 53.5	37.9 ± 6.5	38.0	868	12.0 to 38.5	21.9 ± 6.2	21.5	2529	10.0 to 48.0	25.1 ± 7.2	25.0

UFP: Ultra Fine Particles (measured with the Condensation Particle Counter (CPC) 3007 from TSI Inc.); PM_1: particles less than 1 μm; $PM_{2.5}$: particles less than 2.5 μm; PM_{10}: particles less than 10 μm; CO: Carbon Monoxide; BC: Black Carbon (measured with the MicroAeth AE51 from Aethlabs)*; T: Temperature; RH: Relative Humidity; SD: Standard Deviation. UFP, $PM_{2.5}$ and BC data presented in this table have been post-processed.*

Figure S2 The four villages near Hyderabad (southern India) and the fixed-station ("North Site") where the field-based sampling took place.

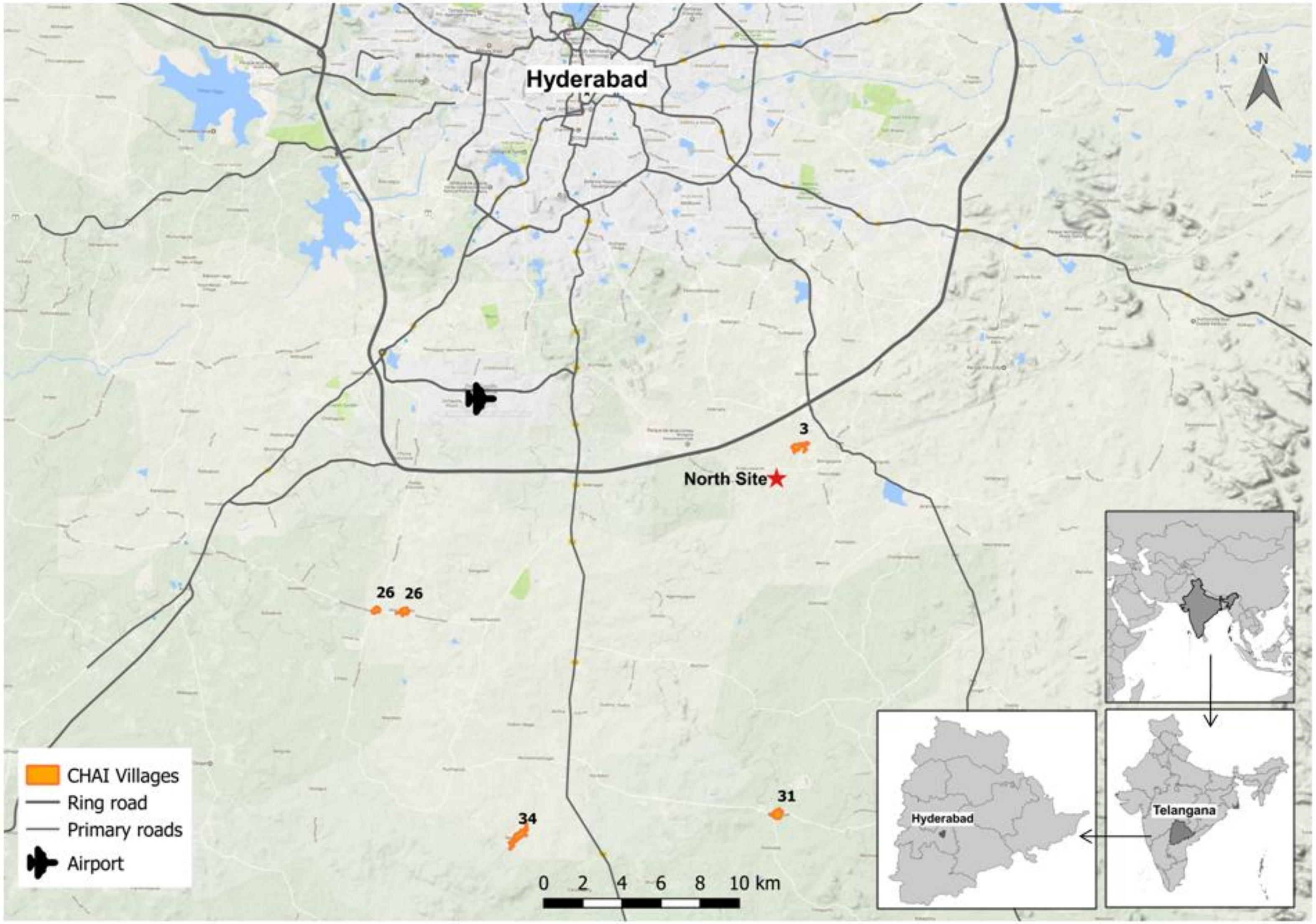


Figure S3 $PM_{2.5}$ levels measured by the benchmark monitor (DustTrak DRX) and the two low-cost monitors (HAPEX, TZOA-R) in the experiment (y-axis truncated at 500 μg/m^3).

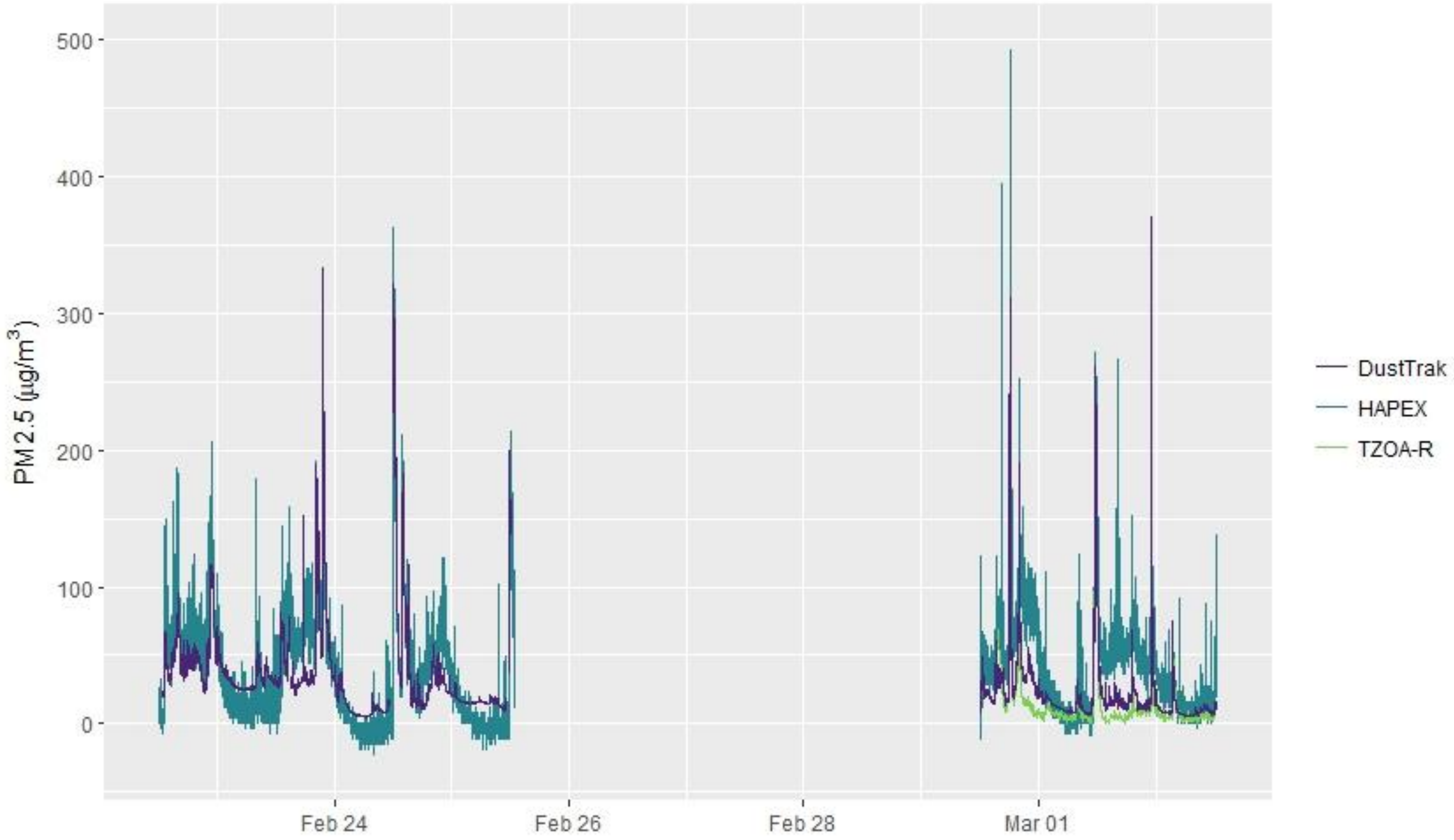


Figure S4 Carbon monoxide (CO) levels measured by the benchmark monitor (Q-Trak) and the three low-cost units (EL-USB-CO) and temperature in the experiment.

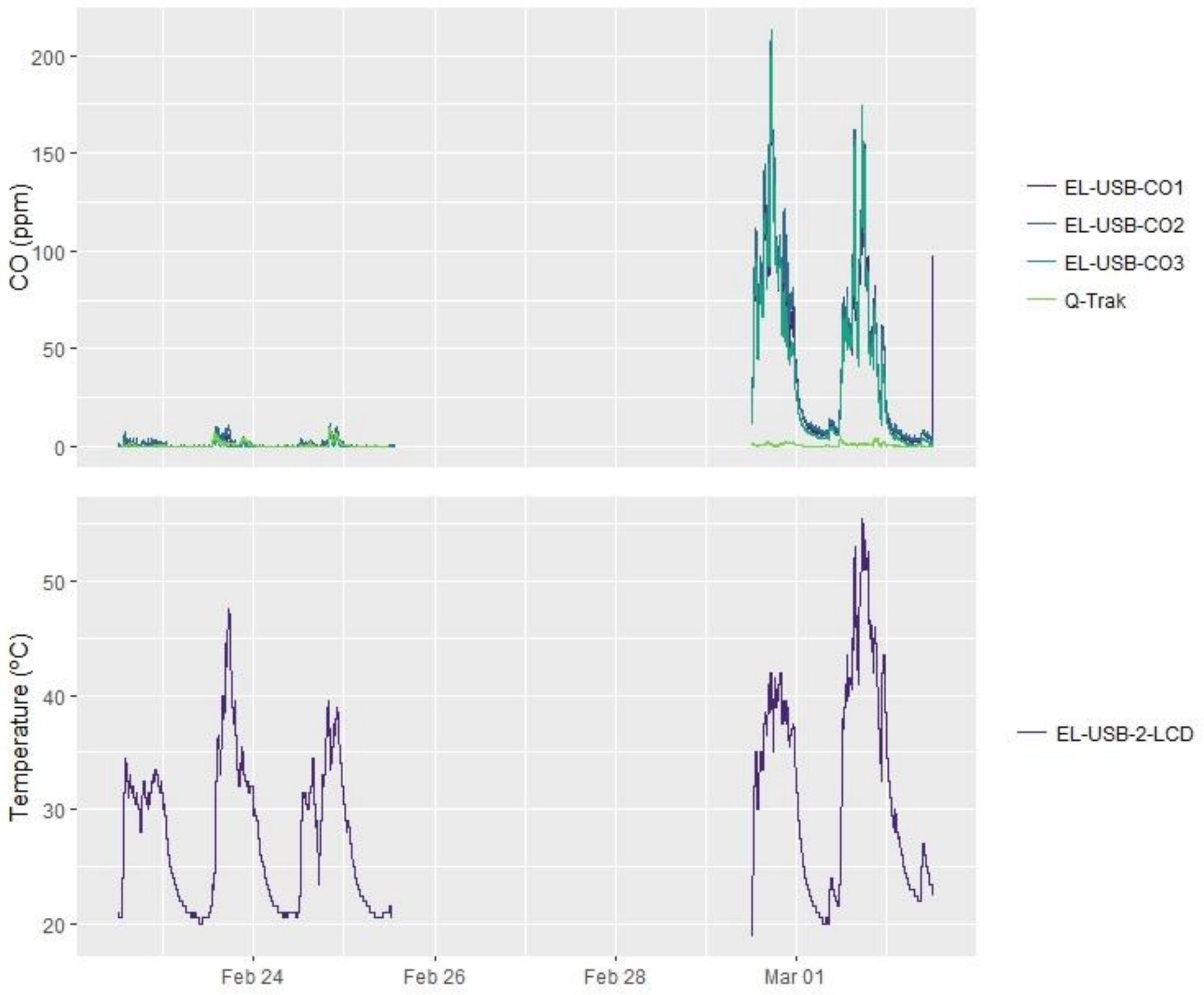
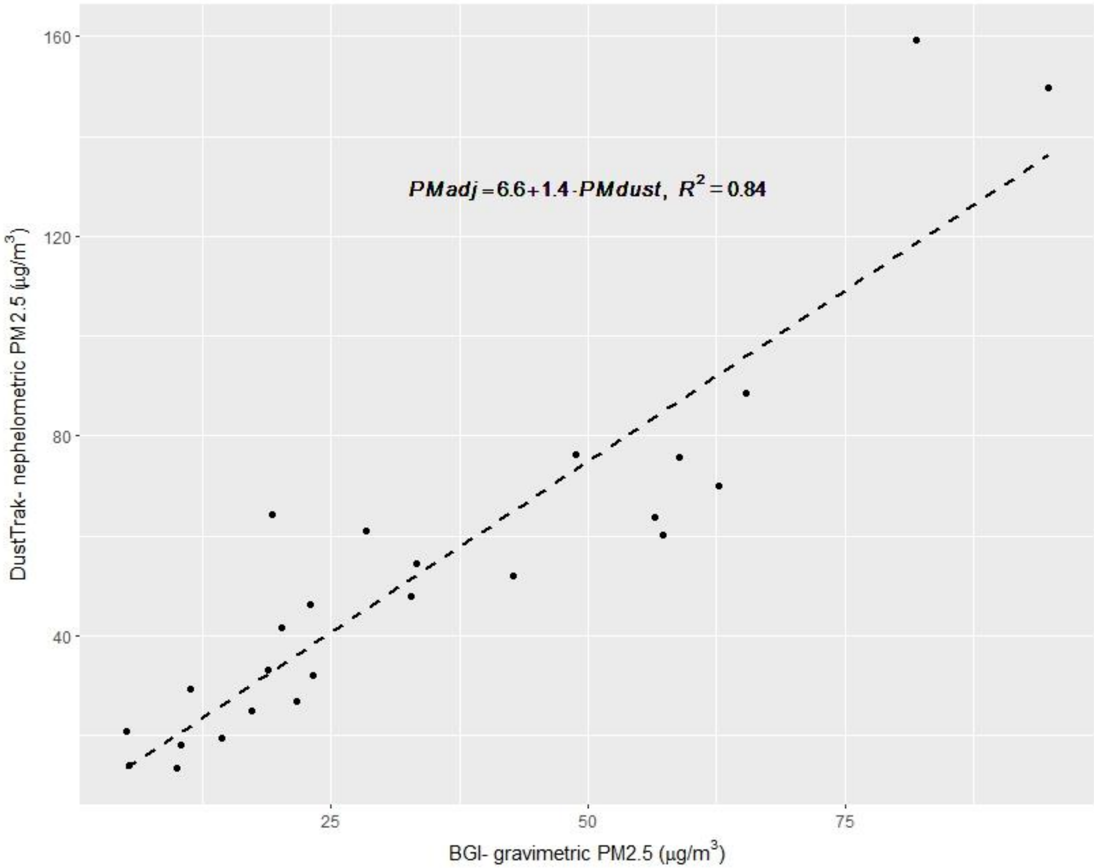


Figure S5 Relationship between $PM_{2.5}$ ($\mu g/m^3$) measured by light-scattering/nephelometric (DustTrak DRX) and gravimetric (BGI pump) sampling.



PMadj= PM adjusted gravimetrically; PMdust= time weighted average (TWA) of DustTrak DRX raw values.

Figure S6 Bland-Altman plot for HAPEX (low-cost) versus DustTrak (benchmark).

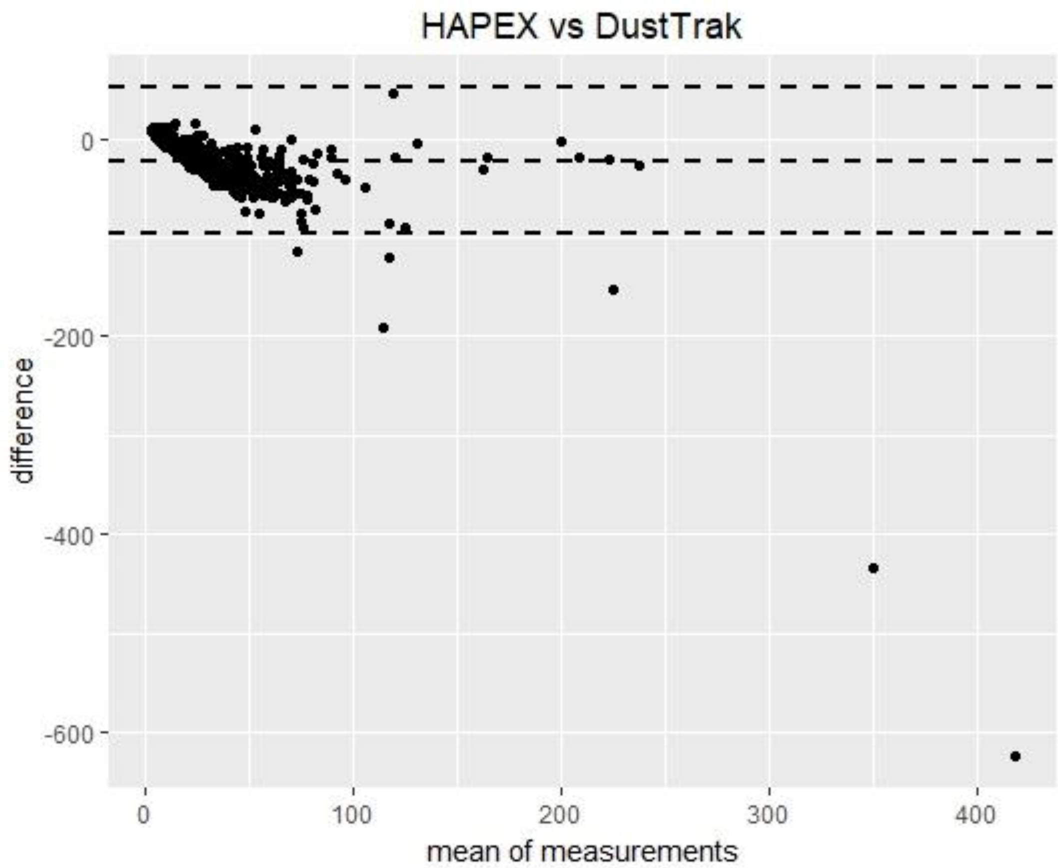


Figure S7 Bland-Altman plot for TZOA-R (low-cost) versus DustTrak (benchmark).

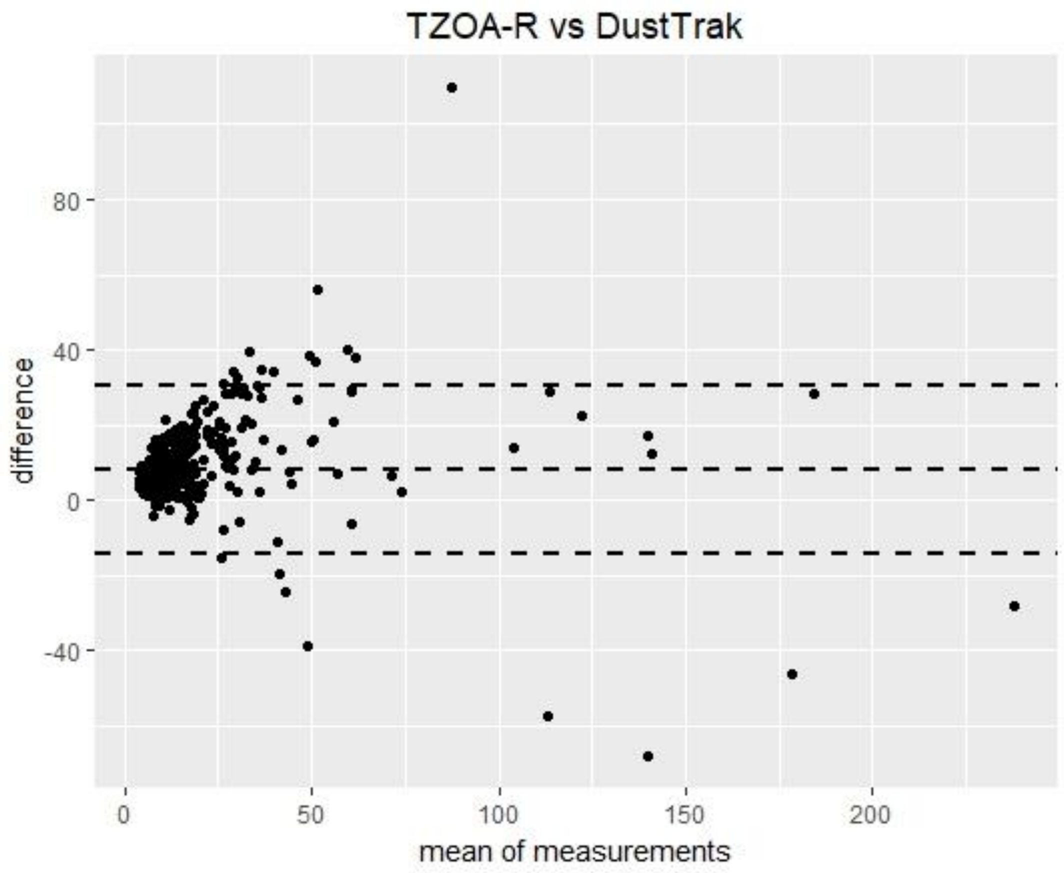


Figure S8 Bland-Altman plot for unit 1 of EL-USB-CO (low-cost) versus Q-Trak (benchmark).

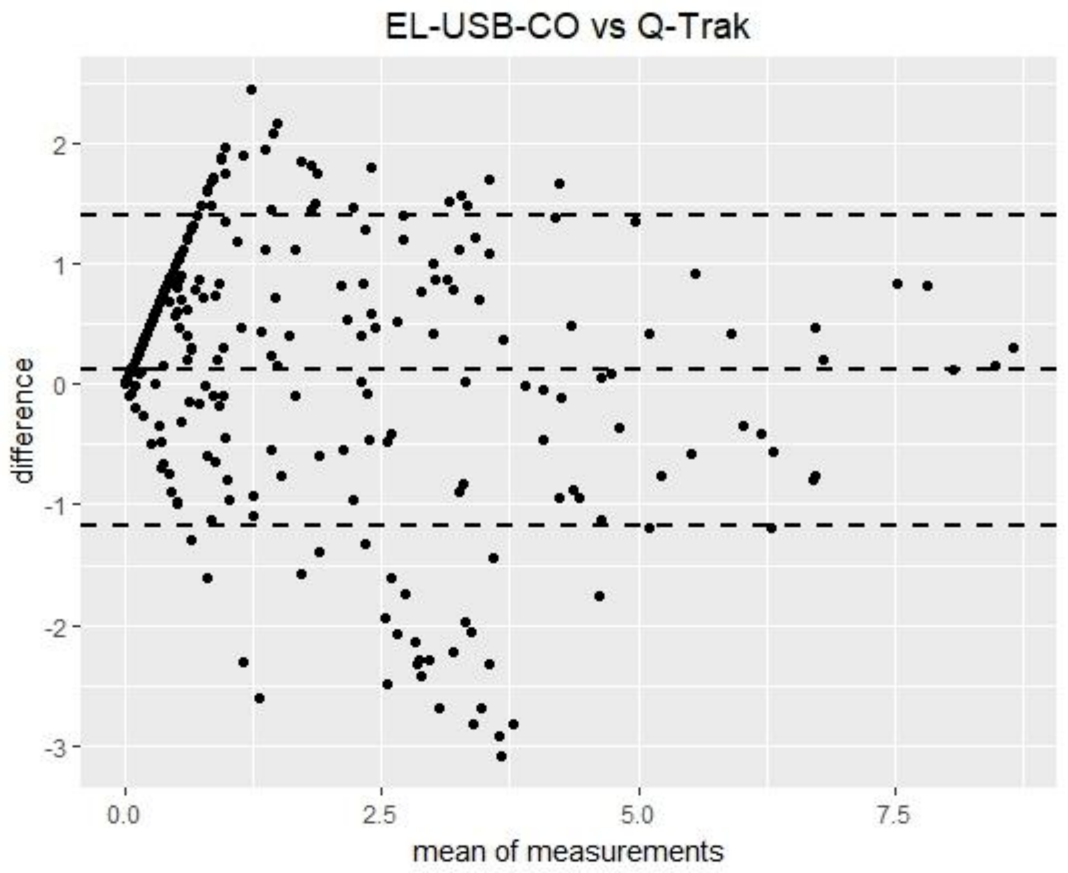
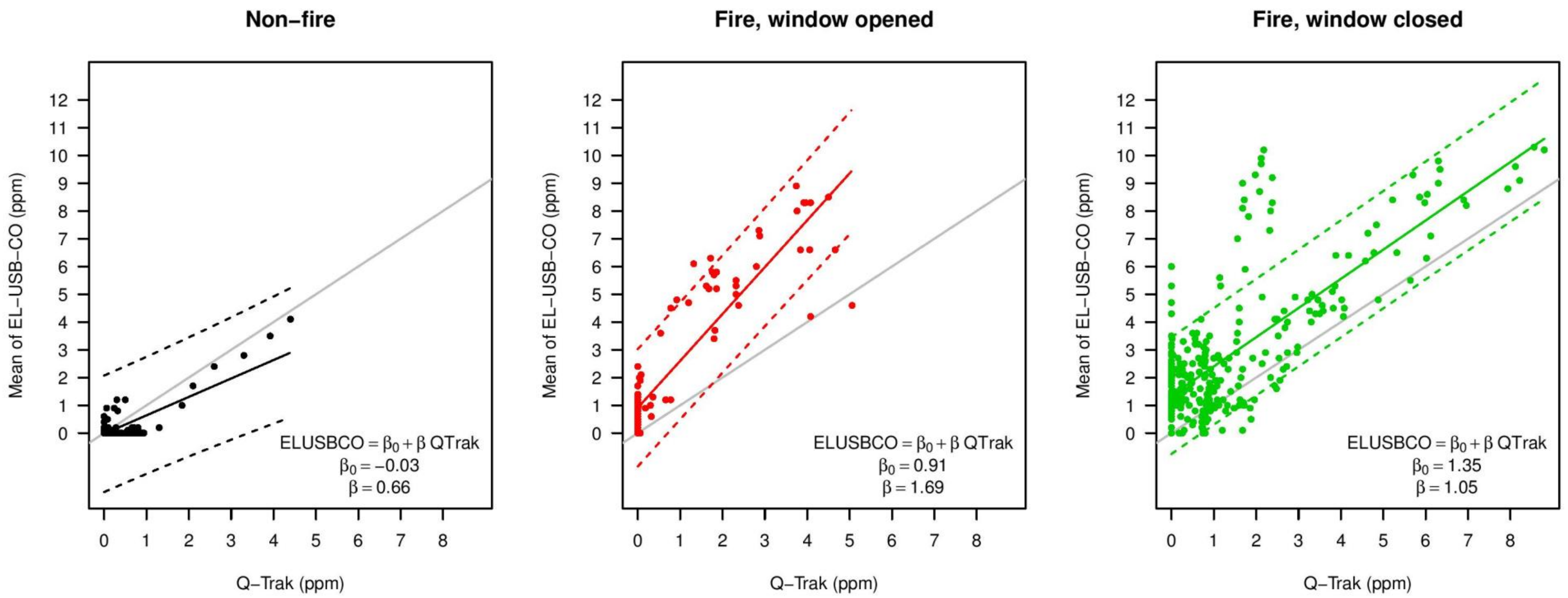
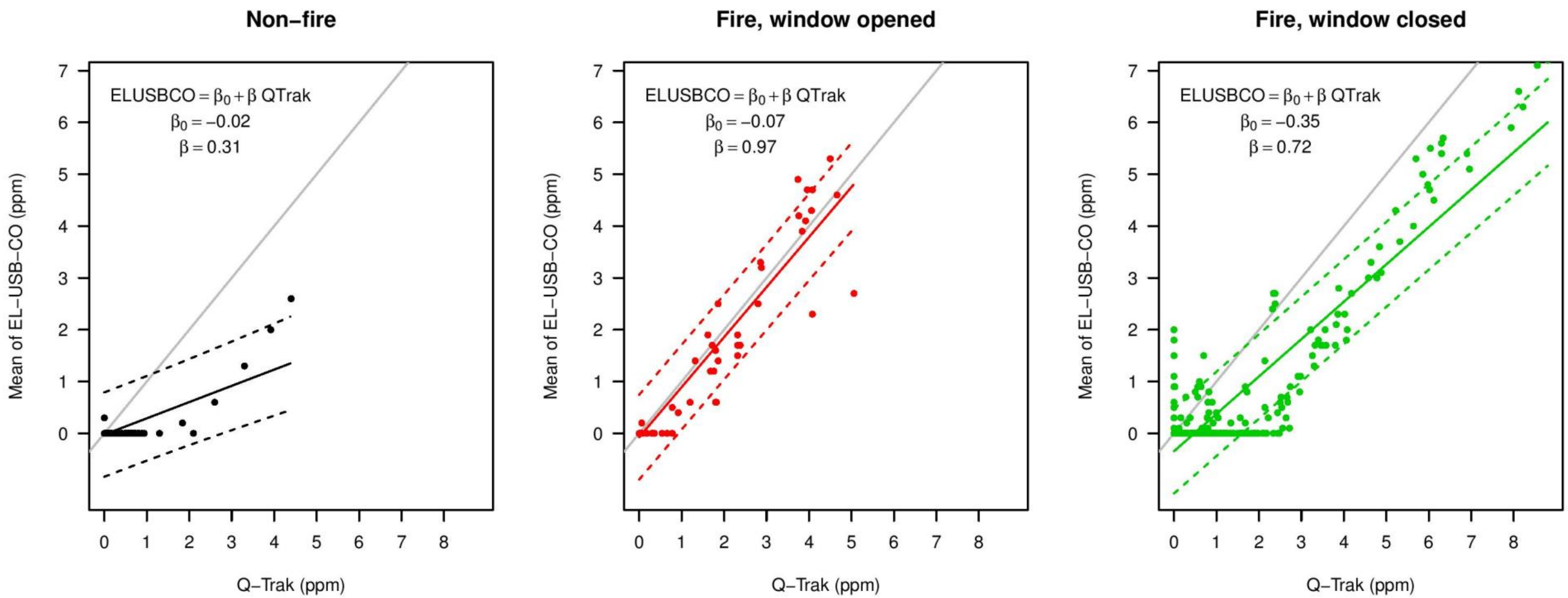


Figure S9 Scatter plots of 5-min CO levels from unit 2 of EL-USB-CO (low-cost sensor) versus Q-Trak (benchmark monitor) during the experiment stratified by fire and room ventilation conditions.



CO: carbon monoxide (in ppm). Plots include only the first three days. Solid lines correspond to the fitted mean concentration of EL-USB-CO. Dashed lines correspond to the 95% confidence interval for the prediction. Grey lines represent the ideal (EL-USB-CO = Q-Trak). The fitted linear model showed an $R^2 = 0.76$.

Figure S10 Scatter plots of 5-min CO levels from unit 3 of EL-USB-CO (low-cost sensor) versus Q-Trak (benchmark monitor) during the experiment stratified by fire and room ventilation conditions.



CO: carbon monoxide (in ppm). Plots include only the first three days. Solid lines correspond to the fitted mean concentration of EL-USB-CO. Dashed lines correspond to the 95% confidence interval for the prediction. Grey lines represent the ideal (EL-USB-CO = Q-Trak). The fitted linear model showed an $R^2 = 0.84$.

Table S3 Adjusted R^2 (in percentage) for the fitted models and partial contribution to R^2 of each term in the model (device, fire and ventilation condition and the interaction between device and condition).

Device	**n[a]**	**R^2 (device)**	**R^2 (condition)**	**R^2 (interaction)**	**R^2 (total)**
HAPEX	1267	42	20	8	70
HAPEX (2 days)	573	43	16	15	74
TZOA-R	463	76	5	5	85
EL-USB-CO (unit 1)	851	71	8	2	82
EL-USB-CO (unit 2)	851	52	22	2	76
EL-USB-CO (unit 3)	851	75	7	3	84

a. "n" represents the sample size of 5-min pollutant data.

MATERIAL AND METHODS (expanded version)

Wood-combustion experiment in Spain

The fireplace was located in the 26-m^2 living room, at 6m from the kitchen area, at 1m from the window and with a ceiling height of 2.5m. All benchmark monitors were plugged to AC power and after 24h, they were stopped, cleaned, zeroed, and synchronized before the following 24-h experiment. In contrast, low-cost sensors ran continuously without electricity supply. Flow-rate of DustTrak DRX was set to 1.7 L/min on each experiment day.

The flow rate of the pump was adjusted at the beginning of each gravimetric round to 3.5L/min with a rotameter (Model RM67, BGI Inc.) and checked at the end of that round to make sure that it had remained at 3.5L/min (±20%) during the course of sampling. Sampled filters were packed individually in 37-mm cassette housings sealed in zipped plastic bags and stored at 4ºC before post-weighing. Both before and after sampling, filters were double weighed with a microbalance of 1 µg accuracy (Model MX5, Mettler-Toledo International Inc., Switzerland) at the facilities of the Scientific Service of Nuclear Magnetic Resonance of the University of Lleida (Spain). A temperature (20-23±2ºC) and humidity (30-40±5%) controlled room was used to condition filters 24h before each weighing session. Quality control included weighing filters two non-consecutive times and discarded both of readings if they differed more than 5 µg. We corrected filters for the mass of 22 field-blanks obtained in the same area using few months earlier the same equipment and following the same protocol.

Field-based pilot study in India

The flow rate of the pump was adjusted at the beginning of each gravimetric round to 1.5 L/min with a flow meter (Model Defender 510, Mesa Labs Inc.) and checked at the end of that round to make sure that it had remained at 1.5 L/min during the course of sampling. Sampled filters were packed individually in 37-mm cassette housings. Both before and after sampling, filters were double weighed with a microbalance of 5 µg accuracy (Model CPA2P-F, Sartorius AG, Germany) at the facilities of the Sri Ramachandra University, Chennai, Tamil Nadu (India). A temperature (21-24ºC) and humidity (42-60%) controlled room was used to condition filters 24h before each weighing session. Quality control included weighing filters a third time only if the two previous readings differed more than 5 µg; if so, the closest two measurements of the three were accepted. All filters obtained were corrected for mass accumulated on field-blank filters (season-specific correction using median blank weight). For more details in the filter weighing and quality control procedures, see Data Supplement 3 of the TAPHE protocol study [1].

REFERENCES

1. Balakrishnan, K. *et al.* Establishing integrated rural-urban cohorts to assess air pollution-related health effects in pregnant women, children and adults in Southern India: an overview of objectives, design and methods in the Tamil Nadu Air Pollution and Health Effects (TAPHE) study. *BMJ Open* **5,** e008090–e008090 (2015).

R script to read raw output files

```
################################################################################################
#### Real-world performance of low-cost sensors to estimate long-term household air pollution ##
################################################################################################

########################################################################################
##  - Reading the raw output files from the low-cost sensors (HAPEX, TZOA-R & EL-USB-CO)
##  - Reading the raw output files from the benchmark monitors (DustTrak & Q-Trak)
##
##  Ariadna Curto & David Donaire
##  ISGlobal-Campus Mar
##  Mar-2016
##  Version 1.0
########################################################################################

##########################
#### LOW-COST SENSORS ####
##########################
#### HAPEX FUNCTION ####
read.hapex <- function(x,tz=Sys.timezone(),...){
  monitor <- paste("hapex",read.csv(x,header=F,nrow=1)[2],sep="_")
  aux <- read.csv(x,skip=11,stringsAsFactors=F,na.strings = "N/A")
  names(aux) <- tolower(names(aux))
  aux$time.stamp <- as.POSIXct(as.POSIXlt(as.POSIXct(aux$time.stamp,format="%m/%d/%Y %I:%M:%OS
%p",tz="GMT"),tz=tz))
  aux <- aux[,1:2]
  names(aux)[1] <- "date.time"
  names(aux)[!names(aux)%in%"date.time"] <-
paste(monitor,names(aux)[!names(aux)%in%"date.time"],sep=".")
  aux
}

#### TZOA-R FUNCTION ####
read.tzoa <- function(x,min=5,...){
  suppressWarnings(suppressMessages(if (!require(data.table)){
    install.packages(pkgs="data.table",repos="http://cran.r-project.org");
    require(data.table)}))
```

```
  aux <- read.csv(x)
  names(aux) <- c("date.time","sample","temp","rh","pm10","ufp","fp","cp")
  aux$date.time <- as.POSIXct(ceiling(as.numeric(as.POSIXct(aux$date.time))
                                    /(60*min))*(60*min),origin="1970-01-01")
  aux$ufp <- aux$pm10*(aux$ufp/100)
  aux$fp <- aux$pm10*(aux$fp/100)
  aux$cp <- aux$pm10*(aux$cp/100)
  aux <- aux[,-2]
  monitor <- paste("tzoa",gsub("(.*_)|(.CSV)","",x),sep="_")
  aux <- data.table(aux)
  aux <- aux[, lapply(.SD,function(x)exp(mean(log(x),na.rm=T))), by=date.time]
  aux <- data.frame(aux)
  names(aux)[!names(aux)%in%"date.time"] <-
paste(monitor,names(aux)[!names(aux)%in%"date.time"],sep=".")
  aux
}

#### USB-CO FUNCTION ####
read.usb.co <- function(x){
  au <-read.csv(x,skip=1,header=F,stringsAsFactors=F)
  aux <- data.frame(date.time=as.POSIXct(au[,2],format="%d/%m/%Y %H:%M:%S"),co=au[,3])
  monitor=paste("usb.co",au[1,4],sep="_")
  names(aux)[!names(aux)%in%"date.time"] <-
paste(monitor,names(aux)[!names(aux)%in%"date.time"],sep=".")
  aux
}

############################
#### BENCHMARK MONITORS ####
############################
#### DUSTTRAK FUNCTION ####
read.dusttrak <- function(x){
  aux <- read.csv(x,sep="\t",row.names=NULL,skip=29,header=F)
  names(aux) <- c("date","time","pm1","pm2.5","resp","pm10","total")
  date.time=as.POSIXct(paste(aux$date,aux$time),format="%d/%m/%Y %H:%M:%S")
  aux <- data.frame(date.time=date.time,aux[,3:7])
```

```
  names(aux)[!names(aux)%in%"date.time"] <-
paste("dust",names(aux)[!names(aux)%in%"date.time"],sep=".")
  aux
}

#### Q-TRAK FUNCTION ####
read.qtrak <- function(x){
  aux <- read.csv(x,sep="\t",skip=32,header=F)
  names(aux) <- c("date","time","co2","t","h","dewpoint","wetbulb","co","bp")
  date.time <- as.POSIXct(paste(aux$date,aux$time),format="%d/%m/%Y %H:%M:%S")
  aux <- data.frame(date.time=date.time,aux[,3:9])
  names(aux)[!names(aux)%in%"date.time"] <-
paste("qtrak",names(aux)[!names(aux)%in%"date.time"],sep=".")
  aux
}
```