Indoor Air Quality in Rural Chinese Kitchens & Village-Scale Clean Energy Interventions

Susan Fischer, Ph.D.
California Air Resources Board
31 July 2007

Acknowledgements

- **USA**: Catherine Koshland (UC Berkeley), John Young (Oregon State), Kathie Hammond (UCB), Kirk Smith (UCB), Bob Spear (UCB); Eric Larson (Princeton), Don Lucas (LBL)

- **CHINA**: Wang GuangZhi, Zhang ZiLiang

- **$**: Berkeleyan Graduate Fellowship, Roselyn Lindheim Award, UC Toxics Substances Research and Training Program (TSR&TP), National Institutes of Environmental Health Sciences (NIEHS) Superfund Basic Research Training Core Fellowship, Princeton University, Wood-Calvert Chair (UCB) in Engineering

Outline

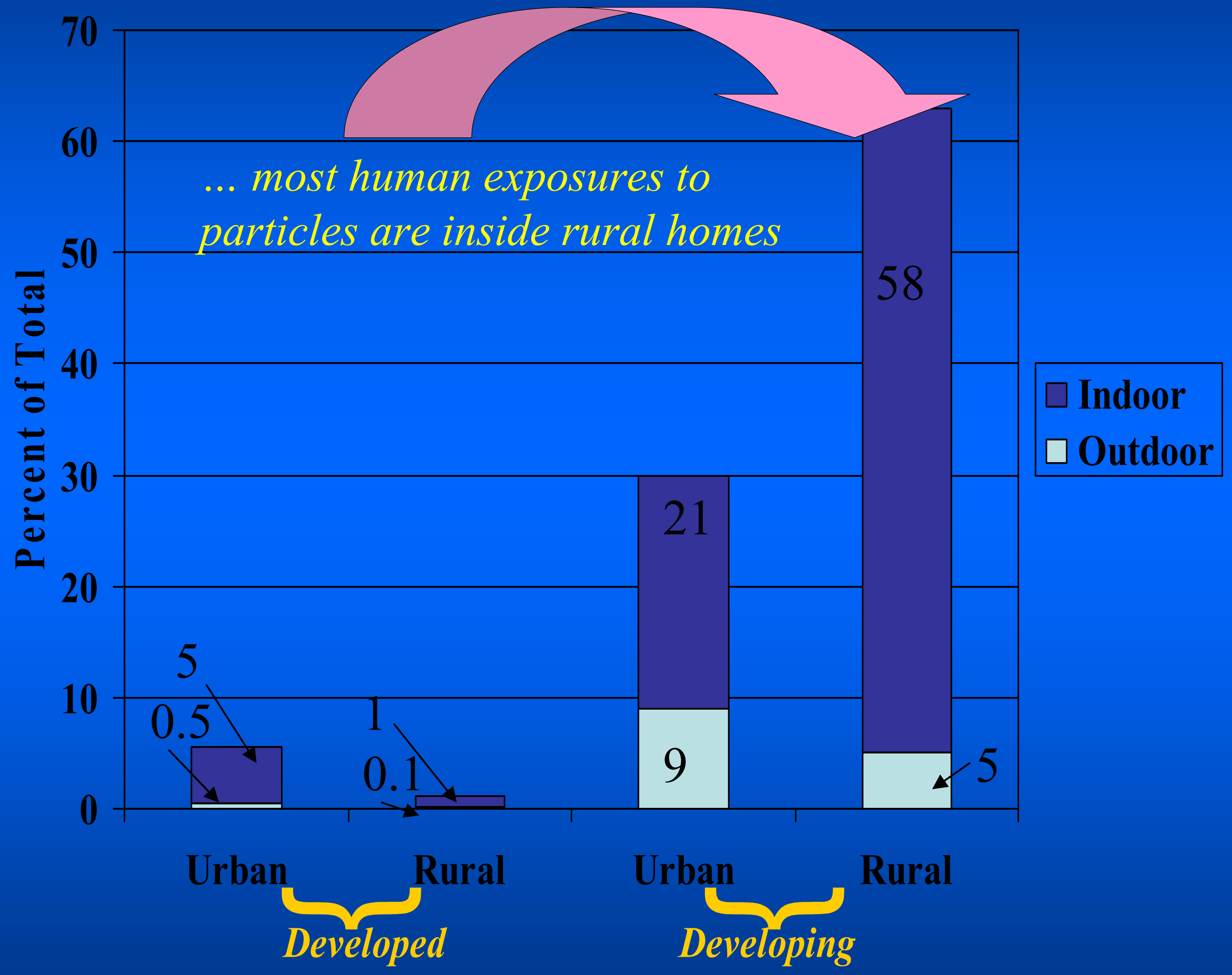
- Rural indoor air quality: global perspective
- Field research in Jilin province, China
  - Use of nephelometer in rural field setting
  - Characterization of indoor air quality and driving factors
  - Case study: three village-scale clean energy interventions

Indoor air quality: a global perspective

- > 3 billion people exposed to pollution from solid fuel combustion indoors[1]
- Solid fuel stoves in China 2-3 orders of magnitude dirtier than gas-burning stoves[2]
- 2-3 orders of magnitude greater inhalation intake per unit emission, indoor vs. outdoor sources[3]

1. World Health Organization (WHO), "Indoor Air Pollution." http://www.who.int/indoorair/en/
2. J. Zhang *et al.* (2000), Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors, *Atmospheric Environment* **34**, 4537-4549.
3. K. R. Smith (1988), Air pollution: assessing total exposure in developing countries, *Environment* **30**, 17.

Global exposures to PM



Source: Kirk Smith (2006). PH200C Introduction to Environmental Health Sciences, UC Berkeley. "General Concepts" Lecture Slides.

Global health burden from indoor air pollution from solid fuels

- >1.6 million deaths per year
- 2.7% of global disease burden
  (*aggregate measure of morbidity and mortality*)
- second largest environmental risk factor

Source: World Health Organization (WHO). *The world health report 2002: reducing risks, promoting healthy life*.
http://www.who.int/whr/2002/en

Jilin
Province
China
International boundary
Province-level boundary
National capital
Province-level capital
Railroad
Road
RUSSIA
KAZAKSTAN
MONGOLIA
KYRGYZSTAN
XINJIANG
XIZANG
QINGHAI
GANSU
NEI MONGOL
HEILONGJIANG
JILIN
LIAONING
SICHUAN
YUNNAN
GUIZHOU
GUANGXI
GUANGDONG
HUNAN
HUBEI
HENAN
SHAANXI
SHANXI
SHANDONG
HEBEI
NINGXIA
JIANGSU
ANHUI
ZHEJIANG
JIANGXI
FUJIAN
HAINAN
TAIWAN
INDIA
NEPAL
BHUTAN
BANGLADESH
BURMA
LAOS
VIETNAM
PHILIPPINES
Aqmola
Barnaul
Semey
Irkutsk
Ulan-Ude
Lake Baikal
Lake Balkhash
Khabarovsk
Hailar
Harbin
Changchun
Shenyang
Vladivostok
Ulaanbaatar
Burqin
Almaty
Bishkek
Ürümqi
Korla
Kashi
Hohhot
Baotou
Beijing
Tianjin
P'yŏngyang
Seoul
Pusan
Dalian
Demarcation Line
Yinchuan
Shijiazhuang
Taiyuan
Jinan
Qingdao
Xining
Golmud
Lanzhou
Xi'an
Zhengzhou
Lianyungang
Yellow Sea
Nanjing
Hefei
Shanghai
Wuhan
Hangzhou
East China Sea
Chengdu
Chongqing
Lhasa
Changsha
Nanchang
Fuzhou
Taipei
Taiwan
Xiamen
Kao-hsiung
Guiyang
Kunming
Nanning
Guangzhou
Hong Kong (U.K.)
Macau (PORT.)
Zhanjiang
Haikou
Hainan Dao
South China Sea
Luzon
New Delhi
Agra
Kathmandu
Thimphu
Lede
Myitkyinā
Mandalay
Hanoi
Chiang Mai
Vientiane
Rangoon
Tropic of Cancer
Chinese line of control
Ganges
Brahmaputra
Huang He
Chang Jiang
TAJ.
AFG.
PAK.


Typical Kitchen in Jilin province, China
(...in the living room: heavy smokers,
possibly another stove)
raw bituminous coal
two solid fuel stoves

Research focus #1

Can a portable nephelometer* be used to measure PM in rural kitchens?

- Time-resolved data needed to characterize exposures and health effects
- Aerosols in rural kitchens highly variable in terms of chemical content, size, relative humidity
- Previous field validations explore relatively low PM concentrations ($PM_{2.5}$ < ~40μg/m^3)
- Previous laboratory validations focus on single-source situations

Instrument to determine particle concentration via light-scattering

Field validation of the personal DataRam (pDR): **key questions**

- How are 24-hr gravitational & optical measurements related?
- How do short-term high humidity excursions affect correlation?
- What are the implications for use of nephelometer in rural indoor studies?

personalDataRAM (pDR): real-time passive particle measurements via light scattering at 880 nm

Fischer and Koshland (2007), Field performance of a nephelometer in rural kitchens: effects of high humidity excursions and correlations to gravimetric analyses, *J. Exp. Sci. Env. Epi.* **17**, 141-150.

Sample

- 65 household-days nephelometer & RH data
  Full range of fuel/stove types, cooking styles, tobacco smoking & heating practices in 224 village homes.
- 23 household-days of gravitational measurements
- Opportunistic sampling from indoor environments dominated by single particle sources:
  - heavy tobacco smoking (n=4)
  - coal-burning stove used for boiling water (n=2)
  - lab-simulated coal-burning fire pit (n=2)
  - non-smoking room in rural Chinese hotel (n=4)

1 household and 2 heavy smoking samples CENSORED due to power failure and tampering with equipment.

Results: Variable optical response ratios between microenvironments

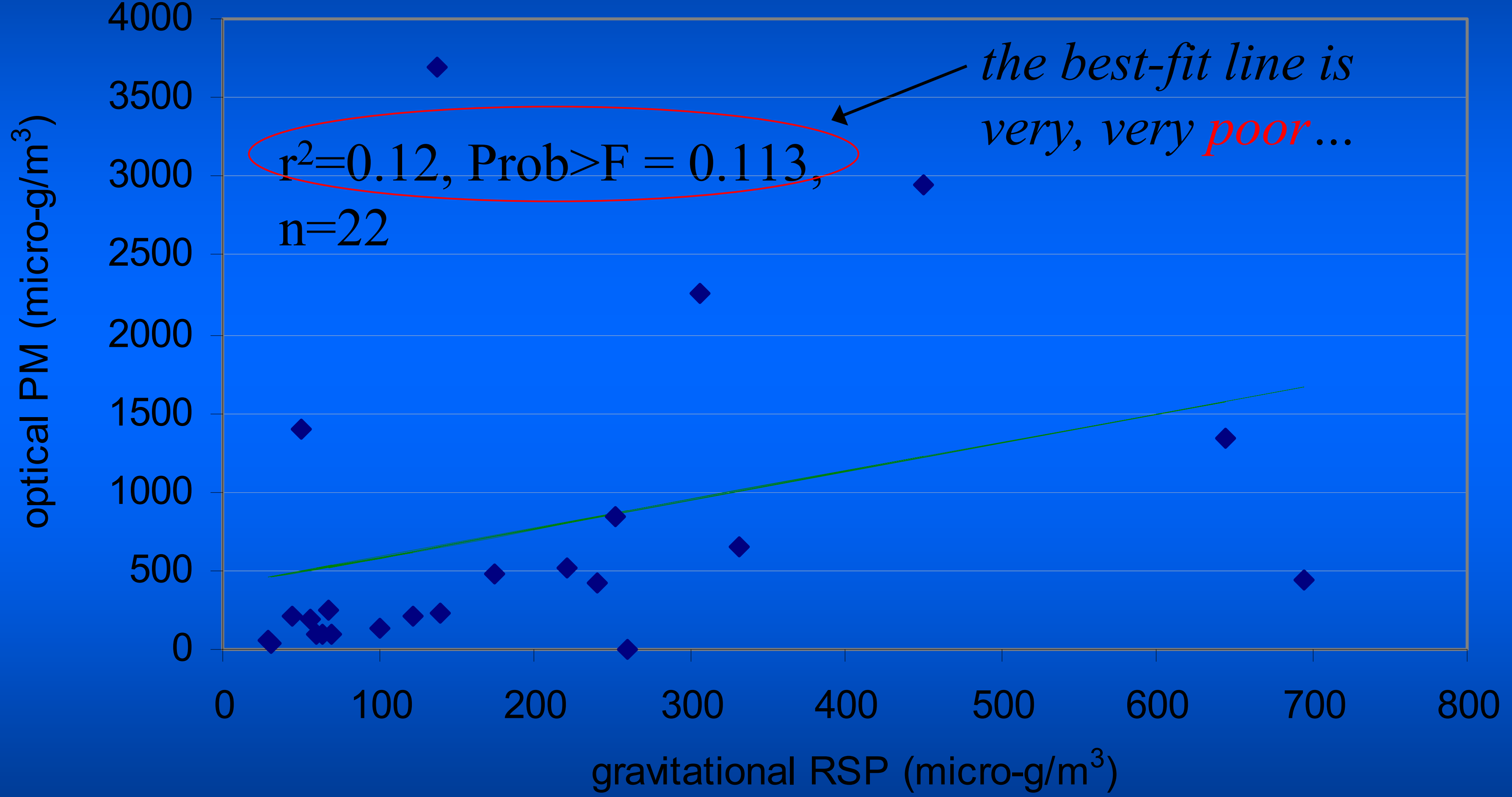
samples plagued by **condensation**

Level	*n*	*response ratio, (geometric mean (GSD))*
kitchen with RH<95% (1-min. resolution)	16	2.13 (1.47)
kitchen with high RH (>95%) excursion	6	7.40 (4.66)
village office with heavy smoking (8-hr.)	2	27.1 (1.55)
solid-fuel coal stove for boiling water	2	0.78 (1.03)
laboratory mock coal fire pit, water boiling, (1.5 hr.)	2	0.91 (1.23)
non-smoking hotel room, Yanbian, China	4	2.30 (1.14)
whole-model test statistics: (Prob>F) <0.0002, r^2=0.59, n=32		

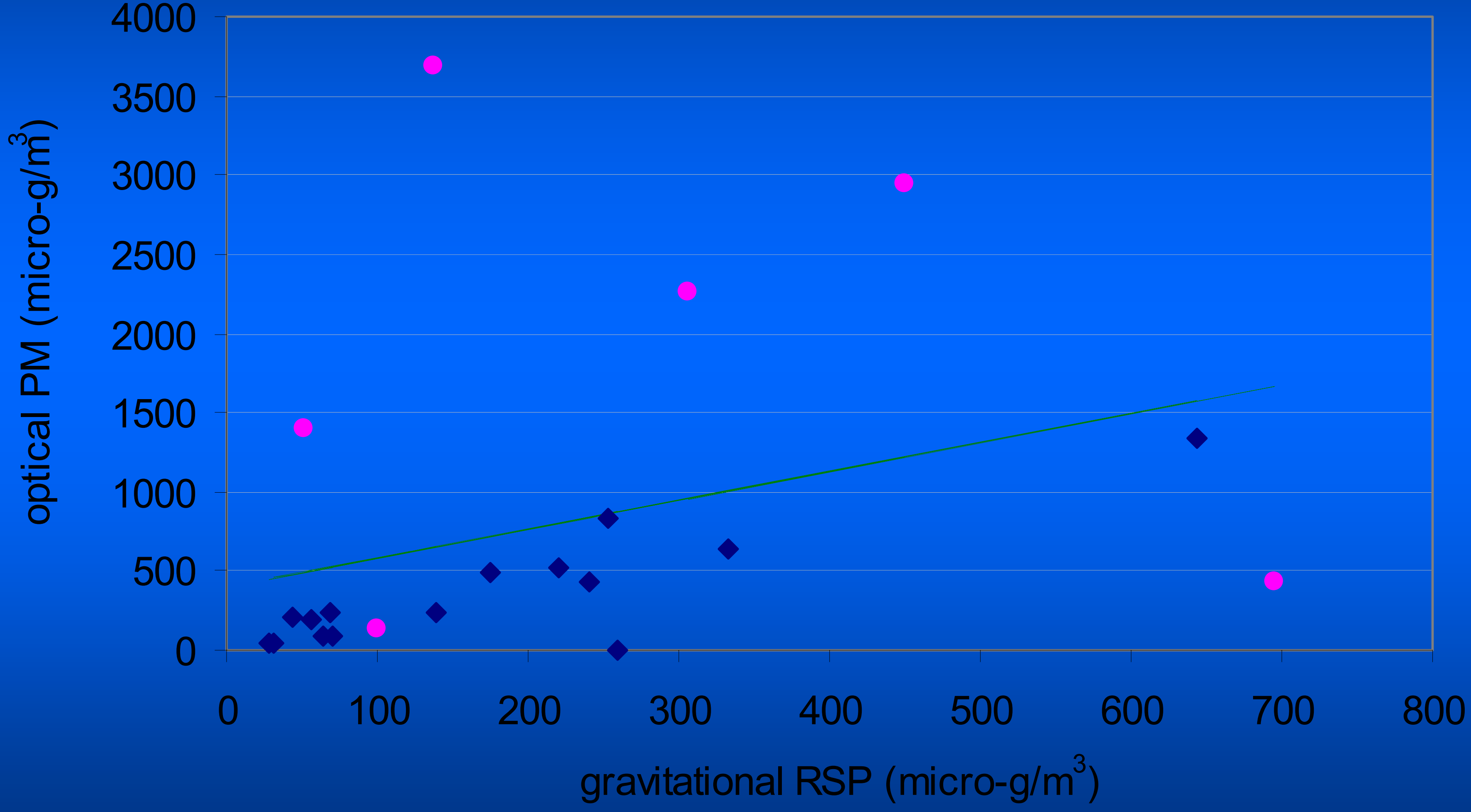
OBSERVED RATIOS OF OPTICAL (*factory calibration*) TO GRAVITATIONAL PARTICLE READINGS: Means and standard errors of mass concentration ratios of nephelometrically determined PM to gravitational RSP.

highly significant test statistics

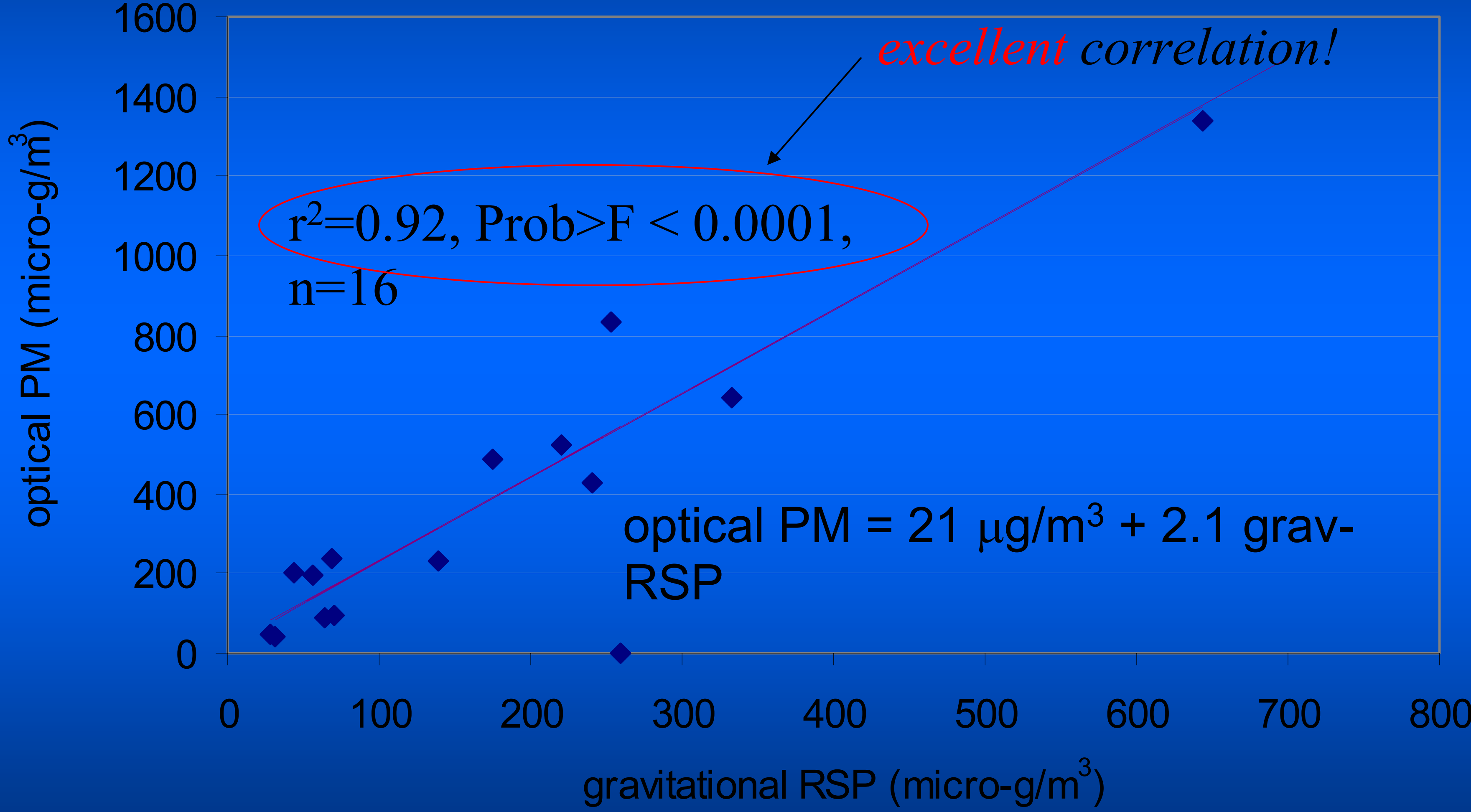
Results: Insignificant correlation between optical & gravitational PM, full dataset



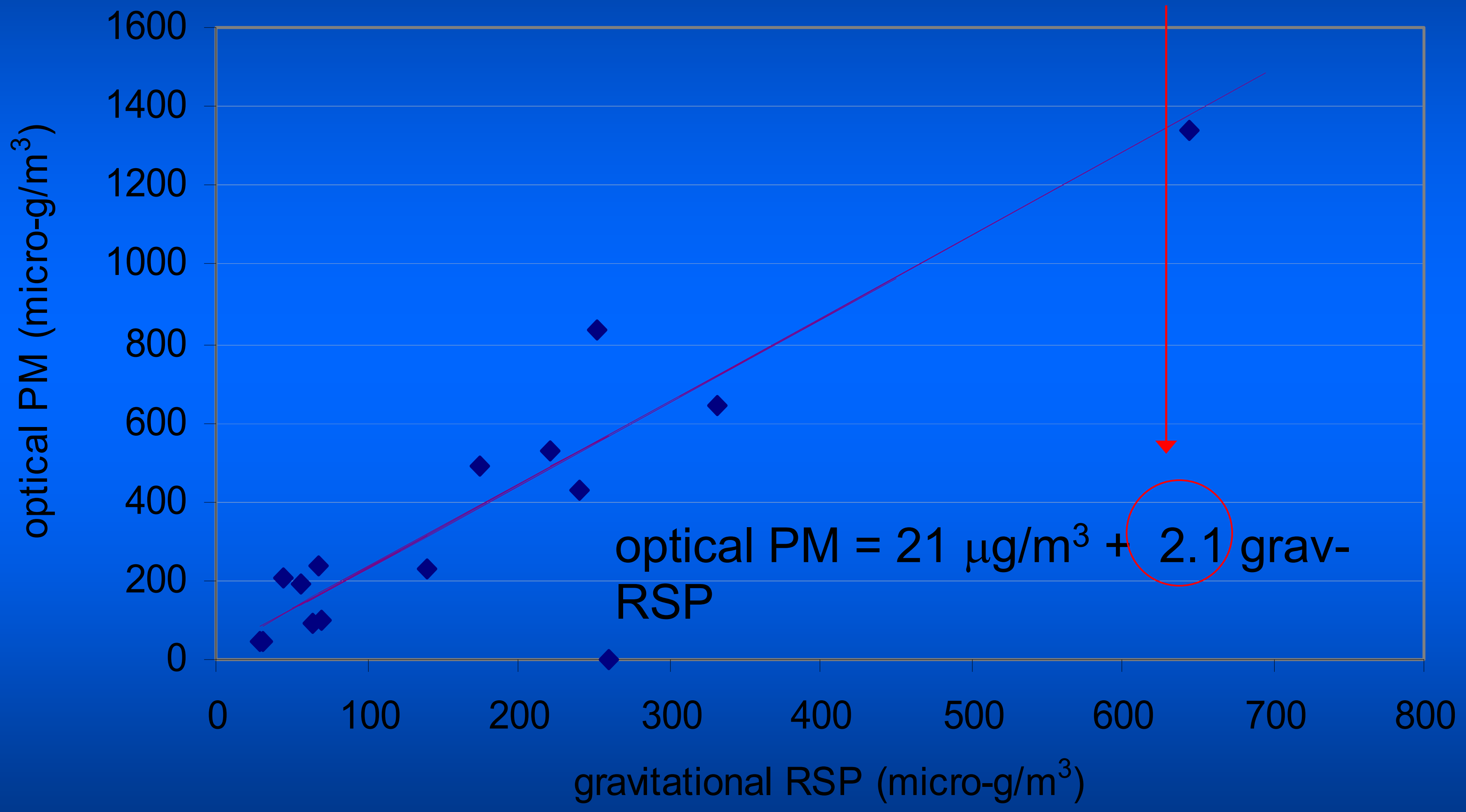
… but 6 (of 22) samples experienced high-humidity (>95% RH) excursions!



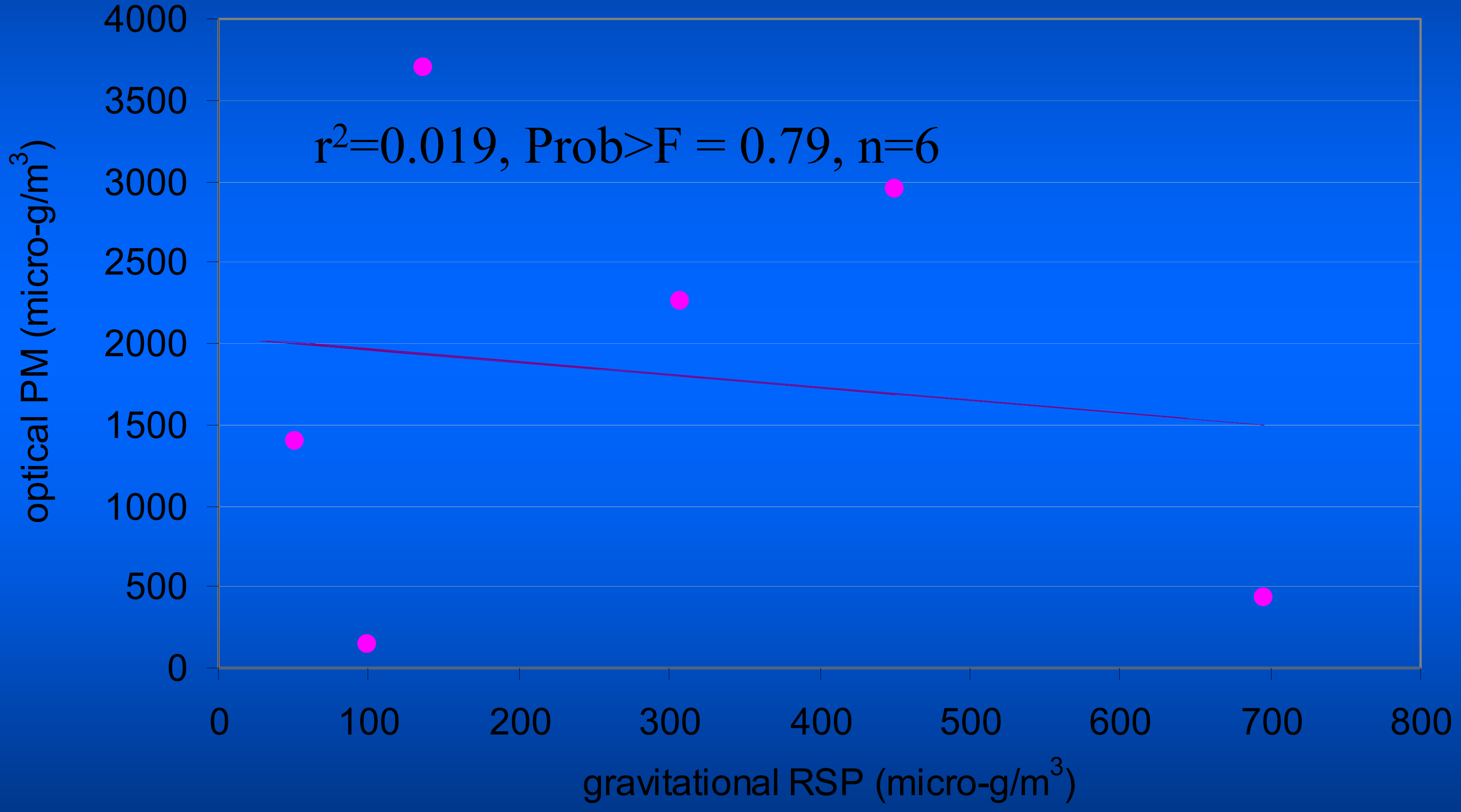
Results: Excluding high-humidity samples reveals a strong correlation



Results: But factory calibration of the nephelometer overestimates by factor 2



Results: No correlation between optical & gravitational in condensing environments



Results: Inclusion of high-humidity samples distorts summary statistics

	ARITHMETIC		*GEOMETRIC*	
	24-hour average PM (mg/m^3)	*24-hr. median PM (mg/m^3)*	*24-hour average PM (mg/m^3)*	*24-hr. median PM (mg/m^3)*
censored (n= 43)	0.312 (0.039)	0.164 (0.032)	0.233 (2.2)	0.099 (2.9)
uncensored (n=58)	0.521 (0.07)	0.148 (0.024)	0.333 (2.7)	0.096 (2.6)
2-way ANOVA: Prob > F, r^2	***0.0019, 0.13***	*0.48, 0.007*	***0.0011, 0.14***	0.88, 0.0003

SUMMARY STATISTICS, CENSORED & UNCENSORED: Summary statistics as arithmetic mean (standard error) and as geometric mean (geometric standard deviation), with ANOVA results for optically determined PM (calibrated to gravimetric RSP). Both arithmetic and geometric means are distorted if samples in which relative humidity exceeds 95% are not censored.

Conclusion: nephelometers promising, but must be used with caution

- Factory calibration overestimates by factor 2 in this setting
- High-humidity samples or dense, poorly mixed plumes create nonsystematic optical distortion
- Conventional measures of central tendency sensitive to distortion when high-humidity samples are not censored
- Previously published rural field work that does not account for humidity excursions or perform gravimetric calibration should be regarded with caution

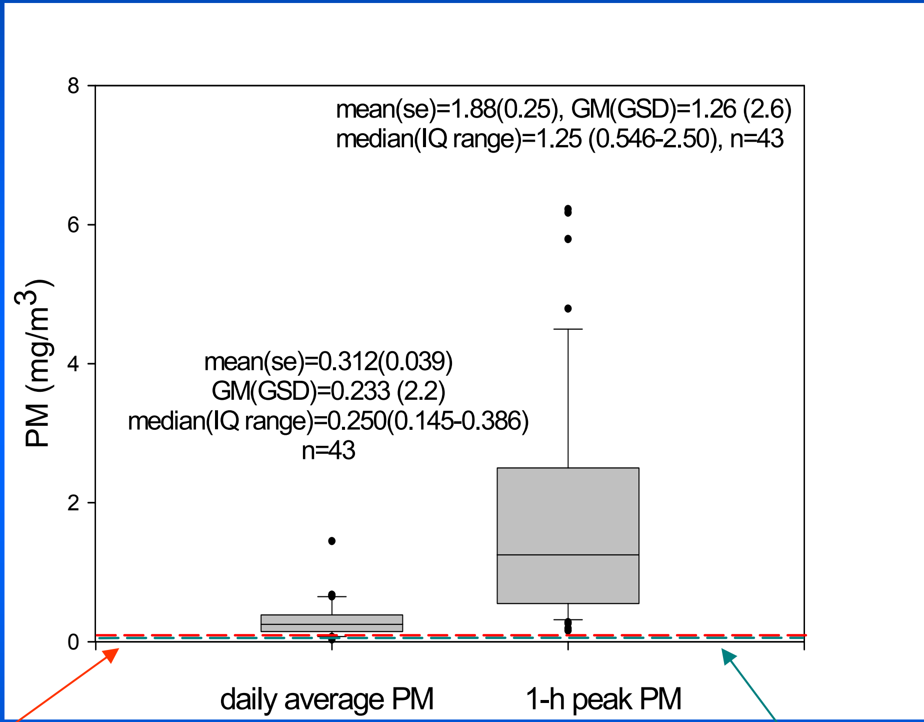
Research focus #2

Indoor air quality and driving factors in a rural Chinese village

- Time-resolved CO and PM data enable characterization of peak pollution periods.
- Diversity of fuels within single village facilitate investigation of fuel- and stove-related factors as well as tobacco smoking as determinants of indoor air pollution.

Fischer and Koshland (2007), Daily and Peak 1 h Indoor Air Pollution and Driving Fcactors in a Rural Chinese Village, *Environ. Sci. & Tech.* **41**, 3121-3126.

Results: Kitchen-area particle concentrations

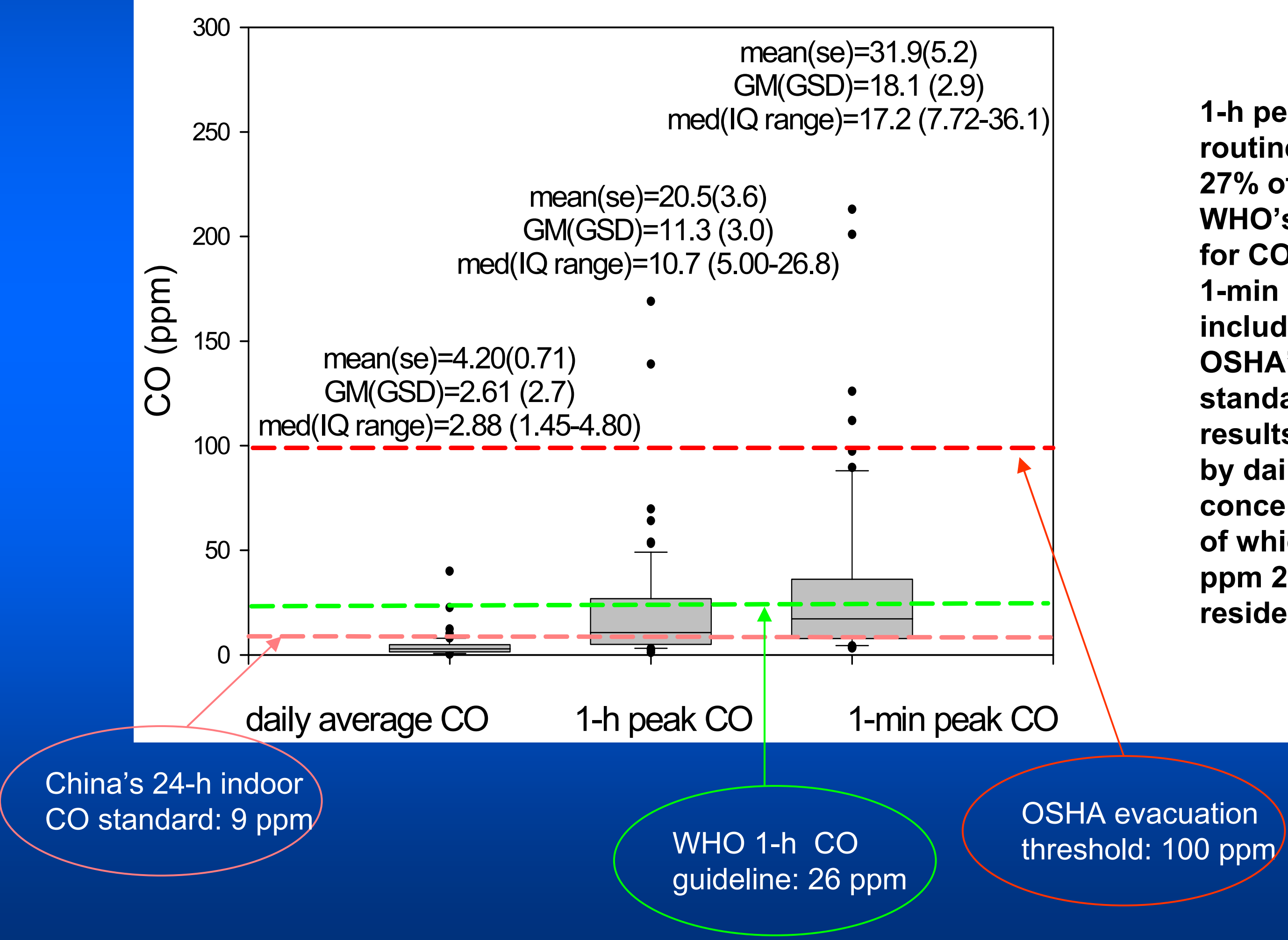


China's 24-h PM_{10} standard: 0.15 mg/m^3

Canada's 1-h indoor PM_{10} guideline: 0.10 mg/m^3

Peak 1-h RSP is six-fold higher than daily average RSP (n=43). Mean daily particle concentration exceeds China's residential indoor PM_{10} standard by a factor of two, and peak RSP is nearly twenty times greater than Canada's 1-h guideline for PM_{10}.

Results: Kitchen-area carbon monoxide concentrations



1-h peak CO concentrations routinely approach, and in 27% of our sample exceed, WHO's 1-h guideline (26 ppm) for CO exposure. Both 1-h and 1-min peak CO samples include exceedances of OSHA's 100 ppm evacuation standard. These alarming results are not foreshadowed by daily average CO concentrations, less than 5% of which exceed China's 9 ppm 24-h standard for residential indoor air quality.

Results: Key factors related to indoor air quality

Tobacco smoke is a significant predictor of peak & daily measures of RSP, but with lesser effect than choice of cooking fuel.

Use of solid fuel for cooking is associated with *cleaner* air in this sample, since villagers use improved fuels as an additional resource rather than as substitute for solid fuels.

Statistically Significant Factors (α=0.05)

factor	*groups (cleanest listed first)*	*IAQ measure*	*differential*	*significance* Ξ
primary cooking fuel	solid, improved (*electricity, LPG, producer gas*)	24-h PM	0.29 mg/m^3	0.04 (<0.0001)
		peak 1-h PM	1.9 mg/m^3	0.03
		24-h CO	5.2 ppm	0.02 (0.07)
		peak 1-h CO	19 ppm	0.02
smoking status	no, yes	24-h PM	0.20 mg/ m^3	0.003
		peak 1-h PM	0.9 mg/ m^3	0.04
primary heating fuel	coal, wood	24-h PM	0.17 mg/ m^3	0.04 (<0.0001)
solid fuel stove in living area	yes, no	24-h CO	2.9 ppm	0.02

At this site, heating with wood fuel is associated with significantly higher daily RSP concentrations than heating with coal.

Ξ Wilcoxin/Kruskall-Wallis test reported in parentheses where different.

Results: Key factors for which no statistically significant relationship was supported

Physically, but not Statistically Significant Factors

factor	*groups*[¶]	*IAQ measure*	*differential*	*sample size*[Ψ] α=5%, β=90%
radiant hot-water heating or second solid-fuel stove in kitchen	present, not present	24-h CO	4.2–4.5 ppm	50–60
		peak 1-h CO	~ 20 ppm	50–60
		1-h peak PM	1 mg/m^3	~40
solid fuel stove in living area	yes, no	peak 1-h CO	14 ppm	~40
smoking status	non-smoking, smoking	24-h CO	1.3	220
		peak 1-h CO	6.1	240

[Ψ] Based on observed distribution & assuming numbers equally distributed between groups.

Results: Key factors for which no significant relationship was suggested

Structural characteristics of kitchen do not predict CO or RSP concentrations in this rural Chinese village.

Factors for which No Significant Relationship Was Observed	
factor	*comments*
kitchen volume	No differential when stratified by tobacco-smoking
kitchen fully partitioned	Fully partitioned kitchen and living areas well-mixe.d with respect to daily (r^2=0.9, $p<0.0001$) and 1-h peak (r^2=0.9, $p<0.0001$) CO concentrations.
total heating time	mean(se)=11.3(1.3) h, range 1.5–24 h
total cooking time	mean(se)=92(6) min, range 40–180 min

Conclusions & *implications*

- Though 24-h CO well within standards, a substantial fraction (27%) of peak 1-h episodes exceed WHO's 1-h guideline & outliers surpass OSHA's evacuation threshold. *Short-term resolution is critical for characterizing acute risks posed by CO exposures in rural kitchens.*

- Adoption of "improved" cooking fuels does not suffice to reduce indoor air pollution where heating dominates fuel use. *Health-oriented interventions limited to provision of improved cooking fuel are insufficient in cold climates.*

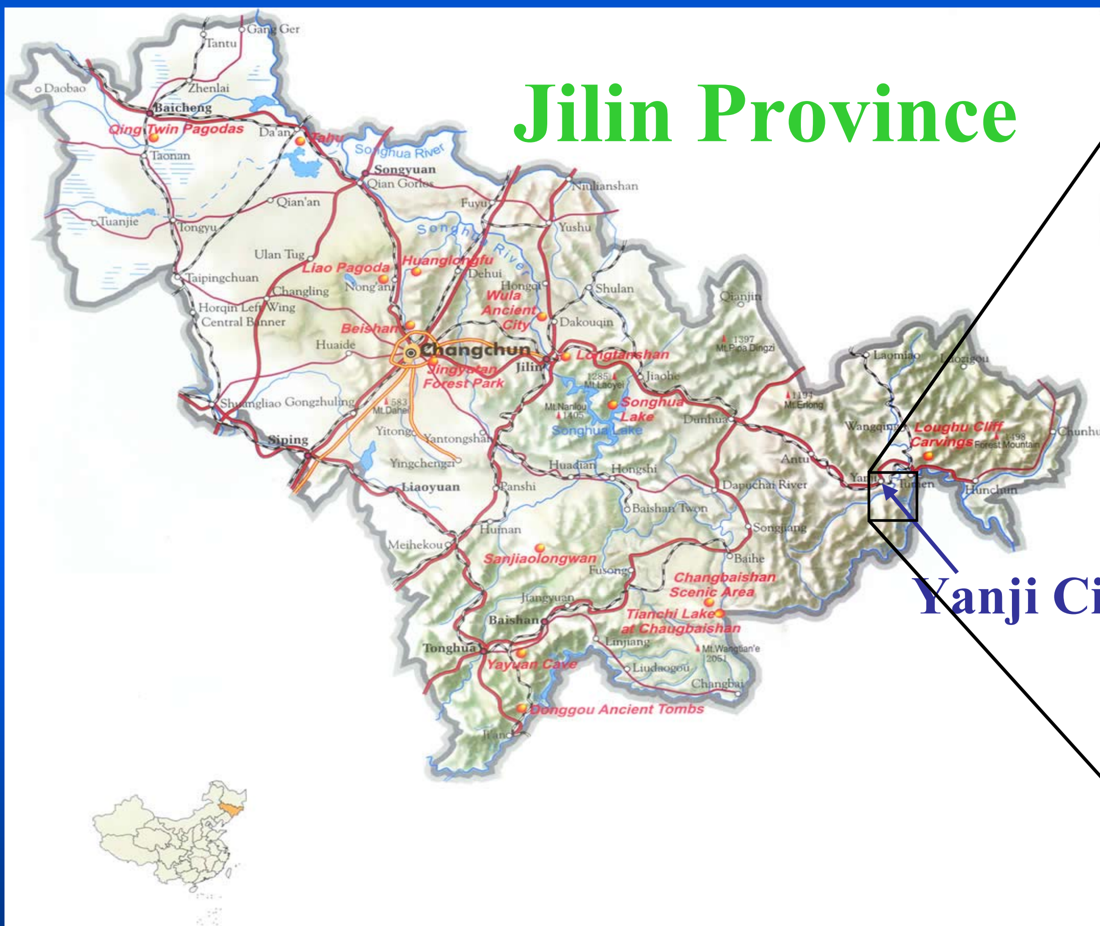
Conclusions & *implications*, continued

- Kitchen and living areas were well-mixed. *In some rural settings, kitchen partitions do not protect people in the living area from acute CO exposures.*

- Heating with wood was associated with significantly more 24-h RSP than heating with coal. The differential (0.17 mg/m^3) was nearly as pronounced as that between smoking and non-smoking (0.20 mg/m^3) households.

Research focus #3

Field investigation of village-scale clean energy interventions



China: a history of rural energy interventions

1958 年 4 月 11 日毛主席视察武汉地方工业展览馆观看沼气灶演示，指示“这要好好地推广”

Being demonstrated of biogas stove on Wuhan local industry exhibition on April 11, 1958, Chairman Mao Zhedong instructed " This should be well promoted"

"This should be well promoted." – Chairman Mao, 11 April 1958

Producer gas projects in China

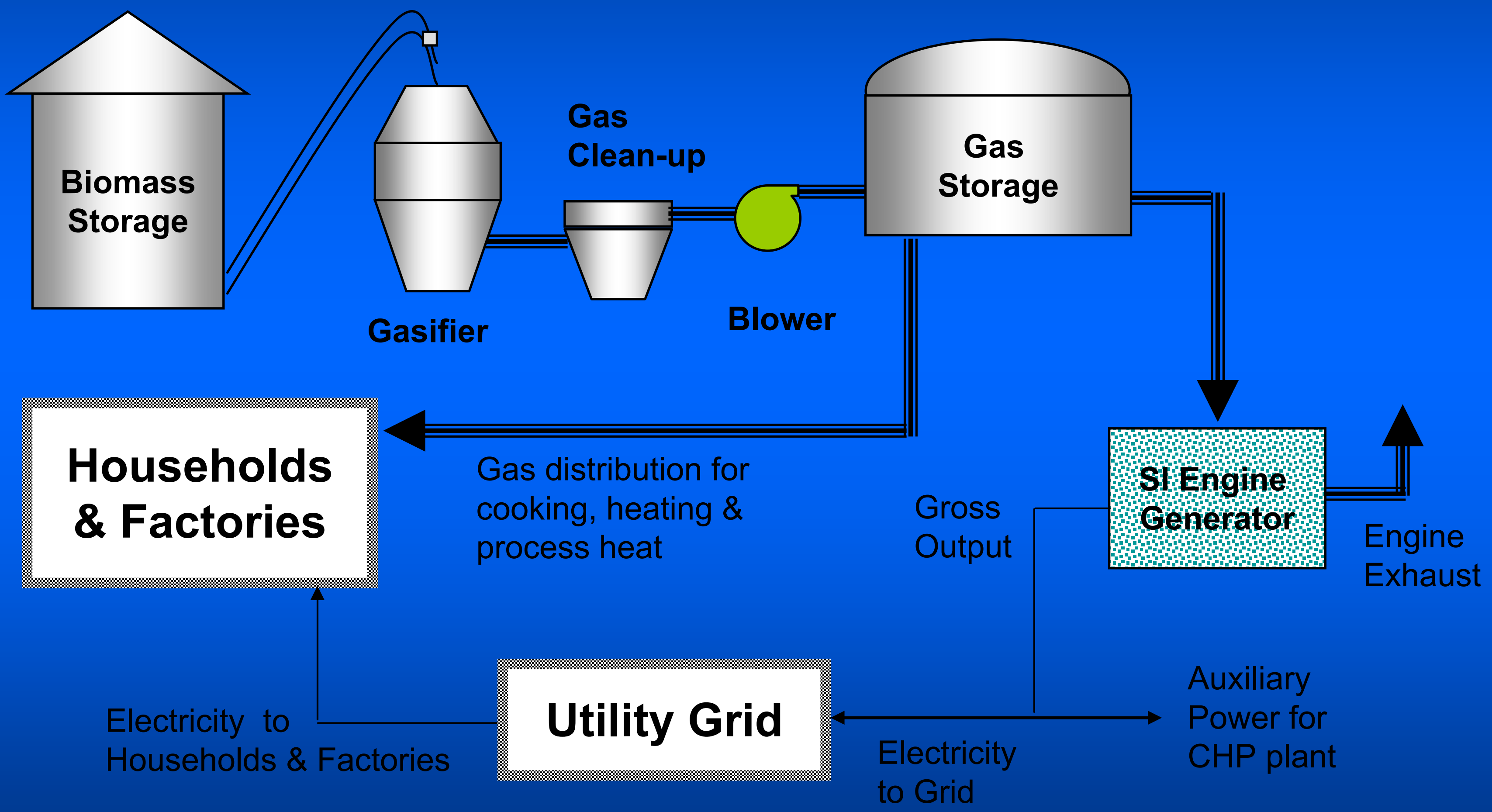
- Chinese agricultural residues could supply cooking fuel for 500-600 million people*
- Hundreds of producer gas§ projects supplying 8,000 households in rural China, year 2000
- 17 village-scale producer gas projects in Jilin

* S. L. Fischer (2001), Biomass-derived liquid cooking fuels for household use in rural China: potential for reducing health costs and mitigating greenhouse gas emissions, *Energy for Sustainable Development* **5**, 23-30.

§ Gas from air-blown gasification of biomass. Approximately 50% N_2, 20% CO, 15% H_2, 10% CO_2, 2% CH_4

Hechengli Village
合成利村

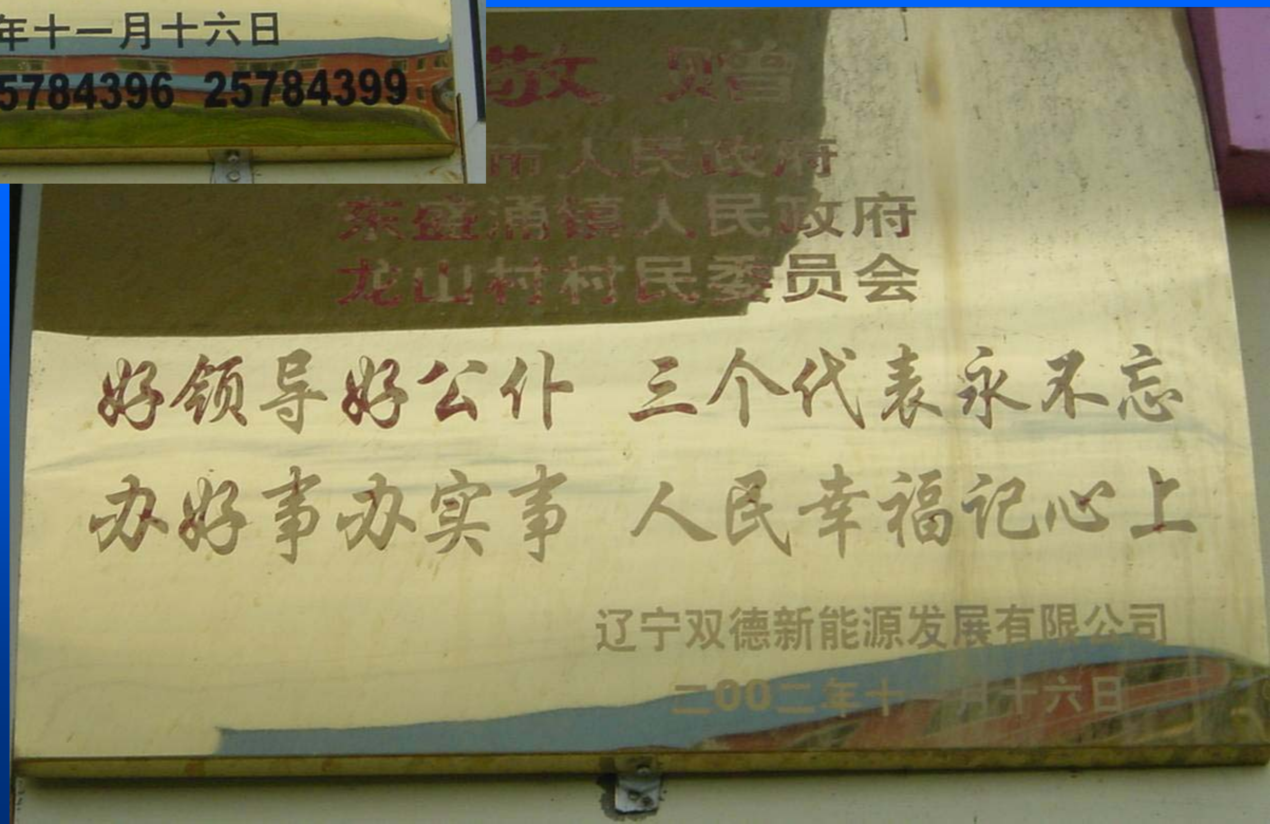
The Hechengli Village Energy Project



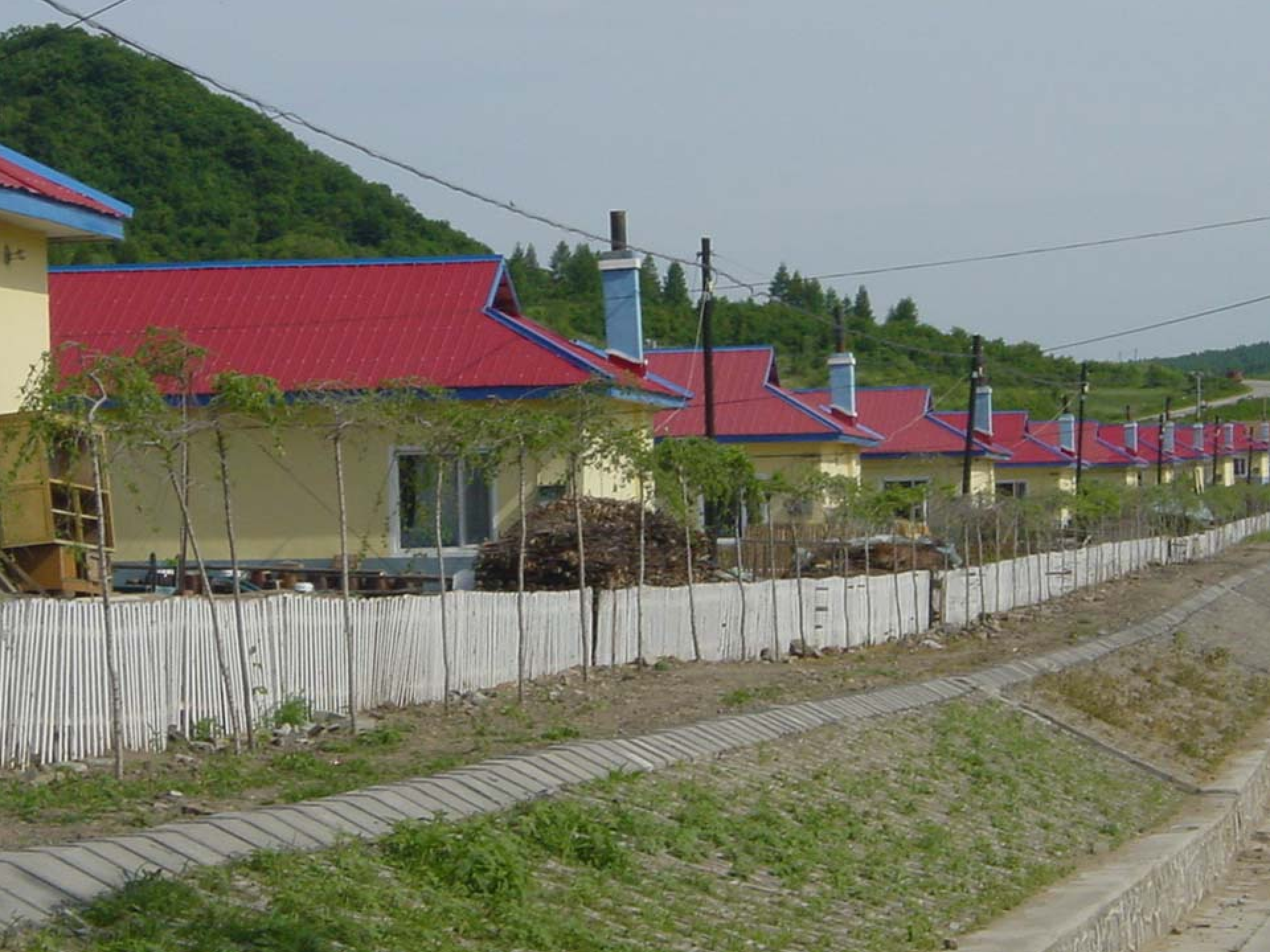

中国吉林现代化生物质能源项目示范工程
Project For Modernized Biomass Energy Jilin China

Longshan Village
龙山村

In operation since
November 16, 2002.



Yongcheng Village
勇成村




兴南小康村

Conclusions from site visits

- Appropriate siting critical to success of factories
- Local capacity to enforce contracts critical
- Project with local leadership fared better than better-funded remotely managed projects set up as demonstrations
- Occupational health concerns not being addressed locally or recognized by provincial/international coordinators

Summary of results

- Nephelometer promising with concurrent relative humidity data and gravitational calibration
- Short-term CO concentrations can exceed guidelines even when 24-h CO is acceptable
- Heating fuel choice, tobacco use important determinants of indoor air quality
- Clean cooking fuel doesn't suffice to mitigate indoor air pollution in cold wintertime households
- Sound business plan, adequate funding, and "appropriate" technology do not ensure a successful village energy project

Additional research

- To support health risk assessment
  - Short-term gravitational sampling concurrent with optical
  - Survey-based approach to assess frequency of rare but statistically & physically (death) significant CO poisoning

- To support fuel interventions
  - Social inquiry regarding household fuel choice, energy-related behaviors
  - Feedback from village projects to provincial and national level administrators and policy-makers