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Household Air Pollution in a Changing Tibet: A Mixed Methods Ethnography and Indoor Air Quality Measurements

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Abstract

Household air pollution (HAP) is considered to be one of the largest environmental health risks in the world, being responsible each year for ~4.3 million deaths globally and 420,000 in China. Tibetan regions of China are known for pristine ambient air but several recent studies have concluded that the indoor air quality in Tibetan homes is compromised. Tibet is changing rapidly and this study sought to holistically understand HAP in relation to these changes. We took 28 measurements of fine particulate matter ($PM_{2.5}$) and black carbon (BC) concentrations in a variety of Tibetan dwellings in the Golog Tibetan Autonomous Prefecture. A semi-structured interview and ethnographic participant-observation were also administered with residents to better understand household behaviors and awareness of HAP. The highest concentrations of $PM_{2.5}$ and BC were found in the traditional yak hair tent, but nomads living in plastic tarp tents with improved stoves and stovepipes also had very compromised indoor air quality. All of the nomads in this study said they would prefer to use a fuel other than yak dung. More nomads expressed concern about their local glacier melting due to climate change than HAP, and indoor trash burning was seen at all sites. This study suggests that raising awareness of health and climate impacts due to HAP, in addition to having a better dialogue among the stakeholders and the residents in Tibet, is essential for obtaining better indoor air quality in the region.

Keywords Household Air Pollution · Tibet · Health · Particulate Matter · Black Carbon · Exposure

Introduction

Three billion people burn biomass—including dung, wood, charcoal, coal and crop biomass—for cooking and heating in the world (Smith et al. 2014). Household air pollution (HAP), primarily due to particulate matter (PM) from such biomass burning in the household, is considered one of the most important environmental health risks, resulting in 4.3 million premature deaths every year (WHO, 2014). Black carbon (BC), the black smoke or soot that arise during the flaring stage of such burning, is important not only because of adverse health effects (WHO 2012, EPA 2012, Grahame et al. 2014), but also because it has emerged as an important player in global climate change. It has been suggested that BC is the second-most important anthropogenic contributor to climate change after CO_2 (Ramanathan and Carmichael, 2008). 18% of BC globally are estimated to originate from residential biomass burning (Bond et al. 2004).

Tibet, located in the southwestern part of China (Fig. 1) is one of the most remote areas in the world and has pristine ambient air quality. Previous studies found very low concentrations of both fine PM ($PM_{2.5}$, those with an aerodynamic diameter of 2.5 µm or less) and BC in Tibet (Chen et al. 2011, Ming et al. 2010), easily meeting the WHO annual air quality standard of 10 µg/m^3. However, due to the burning of biomass in their households in a high altitude, HAP is a serious problem in Tibet. Tibetans have been historically dependent upon dried yak dung as the primary fuel source for heating and cooking, and this is still the case throughout Tibetan regions. Annual consumption of dung is estimated to be 14.3 million tons in Qinghai

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Fig. 1 Top-left map: China mainland with Tibetan-populated provinces in a darker shade, Beijing marked by a red star and Golog TAP marked by a black dot. Zoomed-in map: Tibetan regions (TAR and TAPs with Golog in a darker shade), including a rough breakdown of the three historical/cultural regions of Tibet: U-Tsang, Kham and Amdo

Province and 24.3 million tons in the TAR (Ping et al. 2011). 40% of BC emissions in China are from rural-residential biomass burning (Ni et al. 2014). Previous studies have also posited that BC particles settling on glaciers may be partially responsible for their rapid melting on the Tibetan plateau (Ramanathan and Carmichael, 2008, Xu et al. 2009).

For $PM_{2.5}$, the U.S. EPA has set a 24-h average daily ambient standard at 35 μg/m^3, and the WHO has set a 24-h average daily ambient standard at 25 μg/m^3 with interim targets set at 75, 50 and 37.5 μg/m^3 (WHO 2005).[1] WHO uses the same standards for indoors and it has also created $PM_{2.5}$ emission rate targets (WHO 2014). China has additionally set a national 24-h average indoor air quality standard for PM_{10} of 150 μg/m^3 but has not set an indoor standard for $PM_{2.5}$ (Zhang and Smith 2007). A handful of studies have quantified indoor $PM_{2.5}$ concentrations in other parts of Tibet and recorded average concentrations between 97 and 1670 μg/m^3 (Kang et al. 2009, Li et al. 2012a, 2012b, Chen et al. 2011, Xiao et al. 2015, Gao et al. 2009).

At the same time, lifestyles in Tibet have been changing. First, it is well-known that due to globalizing lifestyle choices and overt Chinese policies—such as the "Restore Grassland Policy" (退牧还草*tuimu huancao*), "Comfortable Housing Project" (安居工程*anju gongcheng*), and "Building a New Socialist Countryside" (社会主义新农村建设*shehuizhuyi xinnongcun jianshe*)—Tibetans have been and continue to be sedentarized into semi- or non-nomadic lifestyles (Yeh 2003). Second, China has continued to pursue improved cookstove programs since the 1980s. In

[1] WHO also has set annual average standards for $PM_{2.5}$ and PM_{10} at 10 and 20 μg/m^3, respectively

2007, the Chinese government further launched the One Solar Cooker and One Biomass Stove Program, specifically in Tibetan regions (the TAR and TAPs) and distributed 79,833 biomass stoves and 244,474 solar cookers over 4 years. In 2012, the China Clean Stove Initiative was launched as a collaboration between the Chinese government and the World Bank. These programs and initiatives resulted in an abundance of improved cookstoves in Tibet. Third, fuel habits in Tibet are changing. Coal has become an increasingly prevalent fuel source as it has been commercialized along with improved stoves (World Bank 2013). Similarly, natural gas is becoming a more prevalent household fuel source in Qinghai Province (Ping et al. 2011). All these changes suggest that HAP should be improving in the region, with better ventilation, better cookstoves, and fuels that burns more efficiently.

We carried out the fieldwork in the summer of 2014 in the under-researched Golog Tibetan Autonomous Prefecture (TAP)[2] within the Qinghai Province to test the hypothesis that HAP varies in households with different lifestyles, cookstoves, and fuel. Our objective was to not only understand HAP levels in households but also assess differences in attitudes and perceptions related to fuel and cookstove uses, as well as their awareness of HAP. In addition to measuring $PM_{2.5}$ and BC concentrations in the households, we also employed a semi-structured interview and ethnographic participant-observation to understand the societal impact of HAP. Women and children are said to be especially burdened by HAP globally (Lim et al. 2012) and within Tibetan homes (Kang et al. 2009, Li et al. 2012a, 2012b, Gao et al. 2009). A disease survey carried out in 2005 in Golog found the greatest burdens of disease to be (from most prevalent to least): digestive issues, respiratory diseases, rheumatoid arthritis, cardiovascular and neurovascular diseases, and infectious diseases. It also found that the prevalence of respiratory diseases is disproportionately high in women and children, and that herders have the highest prevalence of disease by occupation (Zhou et al. 2005). By using ethnography, we hoped to understand if there were differences in the way the Tibetans lived or recognized the problem of HAP, and if HAP affected their lives differently.

We also focused not only on cooking and heating but also on incense sticks and yak butter lamp burning, as the potential source of HAP in Tibet. These neglected sources may serve as important additional pollutant sources into the indoor air, although no attempt has so far been made to determine their contributions.

[2] Sometimes spelled Golok or Guoluo

Methods

Study Site and Participants

The Tibetan people of modern-day China have historically occupied a vast area (2.27 million km^2) that makes up 25% of the Chinese mainland by landmass. Today this region is politically demarcated into the TAR, a province-level division of China and ten TAPs that are located in four provinces (Qinghai, Gansu, Sichuan, and Yunnan) north and east of the TAR (Fig. 1). Six of the TAPs are located in Qinghai, two in Sichuan, and one each in Yunnan and Gansu. The entire area is unofficially divided into three Tibetan regions: U-Tsang in the west, Kham in the southeast and Amdo in the northeast. Each of these regions has unique histories, cultural traits and mutually unintelligible dialects based on the same literary language.

This study was carried out between June and August 2014 in the Golog TAP of the Qinghai Province, a strongly Amdo region. Golog Tibetans are themselves categorized as a unique subgroup with a distinctive subdialect, historically documented as a fierce and rebellious nomadic tribe (Gelek 2002). Today, 91% of Golog's 160,000 residents are Tibetan, the second-highest proportion of all TAPs (Golog Statistical Yearbook 2010). It is presently considered an important region where 'traditional' Tibetan culture and lifestyle persists (Gelek 2002). This region was chosen for study mainly because it showcases the way in which the traditional Tibetan lifeworld is incorporating into the modern Chinese society and economy. The field researcher spent three months in Golog in 2009 and therefore had baseline knowledge of the region.

In order to be eligible for the study, participants needed to be Tibetans who used yak dung as a primary or secondary fuel source in the home. We aimed to measure an equal number of tents and sedentary homes, as well as a few miscellaneous sources and ambient air. In the end, we took samples within one yak hair tent, five tarp tents, four sedentary homes, a prayer room, a school cafeteria, and a teacher's kitchen, as well as in the ambient air. The sample size (N) does not represent the unique number of sites because most (but not all) sites were measured multiple times. Four measurements occurred in a yak hair tent on four different days, seven in tarp tents, and nine in the sedentary homes with concrete structures. A prayer room was sampled twice, a cafeteria once, and a teacher's kitchen was measured three times. Finally, two ambient air quality samples were taken at the roof of a three-story building in a large town. Figure 2 provides representative photos of the different structures. In addition to various structures, different combustion sources were also measured, as shown in Fig. 3. All of the residences used

Fig. 2 Types of residences where HAP was measured: top left, yak hair tent; top right, tarp tent; bottom left, concrete sedentary home

improved stoves, but the yak hair tent used a traditional adobe stove, in addition to an improved stove.[3] Due to logistical challenges, measurements were not always taken during the same exact period of the day, but they were either taken during a period around lunchtime or dinnertime, when the stoves were lit.

The field researcher was heavily reliant on local assistants to locate study participants, obtain consent (forms were written in the local Amdo dialect), and translate during interview administration. Study participants were chosen using a combination of convenience and snowball (chain-referral) sampling, targeting subjects from the acquaintances of the local assistants. Every attempt was made to take measurements at each study site on at least two different days, but this was not possible in every instance due to time limitations and transportation issues.

[3] This paper follows the useful convention put forth by the World Bank (2011): "*Traditional stove* refers to either open fires or stoves constructed by artisans or household members that are not energy efficient and have poor combustion features. *Improved cookstove* is used in the historical sense for stoves installed in "legacy" programs, usually with a firebox and chimney, but without standards and with poor quality control."

Quantitative Measurement of $PM_{2.5}$ and BC Concentrations

Two instruments were used to measure real-time levels of $PM_{2.5}$ and BC. $PM_{2.5}$ concentrations were measured using the DustTrak II Aerosol Monitor 8530 (TSI Inc., range: 0.001–400 mg/m^3, resolution: ±0.1% of reading or 0.001 mg/m^3) at a 3.0 L/min flow rate. The DustTrak recorded a measurement every minute. Additionally, we measured the concentration of BC using the microAeth AE51 (AethLabs Inc., range: 0–1 mg/m^3, resolution 0.001 μg/m^3) at 50 mL/min flow rate with a $PM_{2.5}$ size-selective inlet. Measurements were recorded every 5 min.

The two instruments were always positioned in a similar fashion in a location that closely approximated residents' sitting and breathing location. The intake tubes of the DustTrak and microAeth were always propped together so that both were sampling air parcels within a 1–2-inch radius. The battery life of the DustTrak and logistical constraints of recharging limited measurement periods. Twenty-six out of the 28 measurement periods were between 3 and 4.5 h. The two shorter measurement periods were 2.25 h and 1 h.

Fig. 3 Various combustion sources where HAP was measured: top left, improved stove in a tarp tent; top right, traditional adobe stove beside an improved stove in yak hair tent (note how stovepipe terminates inside tent); *middle left*, teachers' kitchen; middle right, different type of improved stove in cafeteria kitchen; bottom, yak butter candles in a prayer room

Semi-Structured Interview

A semi-structured interview was carried out once in each residential site where air quality was measured with consenting adults. The interview guide can be found with the Supplementary documents. The questions were adapted from Xiao et al. (2015) and designed to gain a sense of household demographics, stove use patterns, fuel use habits, and health concerns in the home. This was a semi-structured interview because some questions were open-ended and the interviewee was allowed to carry questions in unplanned directions with approval. If the interviewee began to talk about a relevant topic of interest, the interviewer was free to ask follow-up questions before returning to the interview guide. It was administered in the Amdo Tibetan dialect with a translator, transcribed in English and later analyzed.

Ethnographic Observation

The field researcher—having worked previously in Golog, studied the language as well as Tibetan culture and history, and trained and practiced ethnographic techniques—was well-positioned for "deep hanging-out," as anthropologists often characterize ethnography (Clifford 1996). Given the privilege to eat and sleep alongside study participants, the researcher was able to gain a more holistic understanding of household air pollution in Tibet. This is not a methodology often employed for HAP studies but we believe it is useful for finding an effective mitigation measure. We need to understand socio-contextual ontologies, behaviors, and economies operating at the household level, and ethnography provides the tool and lens that allowed us to access this context.

Throughout the quantitative data collection periods, the field researcher kept detailed observational field notes relevant to air quality, such as when fuel was added to the stove, what kind of fuel was added, when a cigarette was lit inside, and how the smoke looked/smelled at notable times. In most instances, the field researcher was asked to visit or live with study participants beyond the daily battery capacity of the measurement devices. The researcher was also invited to take part in household practices—such as collecting and spreading fresh yak dung or fetching dry yak dung from outside caches. Such participant-observation allowed the researcher to write extensive ethnographic field notes and gain relevant knowledge to better understand the residents' awareness of HAP and their impacts.

Results

By the end of data collection, 28 measurements had been taken in a variety of settings and nine semi-structured interviews were conducted. Meteorological conditions varied widely across the study period. At elevations over 4000 m, temperatures still dipped below freezing and snow fell up until mid-June. By late July, temperatures on a cloudless day could soar between 20 and 26 °C.

$PM_{2.5}$ and BC Concentrations

Table 1 shows that average indoor $PM_{2.5}$ concentration levels in Golog are orders of magnitude higher than the 24-h average WHO guideline of 25 $\mu g/m^3$ and China's National Ambient Air Quality standards of 75 $\mu g/m^3$ (WHO 2014). Only the ambient measurement fell below the standard. The average $PM_{2.5}$ concentration inside tents and sedentary homes during sampling periods was 2286 $\mu g/m^3$ and 509 $\mu g/m^3$, respectively. Stratifying by tent type, tarp tents showed an average concentration of 755 $\mu g/m^3$, and the yak hair tent showed 4,964 $\mu g/m^3$. The teachers' kitchen was set up in a very similar manner to a sedentary home—and in fact the cook lived and slept in the kitchen—but it was categorized separately because it represents a 'workplace' exposure for the teachers who spend time in there during breakfast, lunch, and dinner. This kitchen was measured on three occasions and had an average $PM_{2.5}$ concentration of 880 $\mu g/m^3$. The single school cafeteria measurement was taken in the cafeteria-style kitchen, which was connected to the eating-space by a door and pass-through window, and it had an average $PM_{2.5}$ concentration of 55 $\mu g/m^3$. The prayer room in which yak butter lamps and incense were burned had an average $PM_{2.5}$ concentration of 76 $\mu g/m^3$ across two measurement periods.

High instantaneous concentrations were recorded across all sites, which are also shown in Table 1. The maximum instantaneous $PM_{2.5}$ concentration in the yak hair tent reached 157,000 $\mu g/m^3$, at which time the visibility in the tent was reduced to ~ 3 m—one could not see from one side of the tent to the other. Table 2 provides observational context for each of the maximum instantaneous concentrations. Most of the maximum values correspond with a time when the fire is being built-up and stoked in preparation for making a meal and/or tea. The BC concentration levels represented between 0.32–4.74% of total $PM_{2.5}$ concentrations. In general, as $PM_{2.5}$ concentrations decreased, BC accounted for a higher proportion of the total PM content, as shown in Table 1, illustrating a higher rate of complete combustion.

Semi-Structured Interview Results

Findings from the nine semi-structured interviews are presented in Table 3. Interviews were conducted with residents in four tents (three tarp tents and one yak hair tent) and five sedentary homes. All of the homes and tents used an improved stove, including the yak hair tent, which used both an improved and a traditional adobe stove. Tent dwellers seemed more likely to indicate that they use the stove all day unconditionally, while all sedentary home residents said that the stove was only used during certain meal times (usually breakfast and dinner), or it was used less frequently in the summer. For those living in the yak hair tent, the traditional adobe stove was mainly used in the background and the improved stove was for utility, such as for making tea and for cooking. On average, the sedentary homes had older improved stoves, and the residents have been using a stovepipe for one year longer than those in the tents.

The ability to use alternative fuel (e.g., natural gas or coal) in addition to yak dung indicated a certain income level among the residents in the region, in addition to the type of residence they lived in. All of the tent residents used yak dung as the primary fuel source year-round, while one of the sedentary home residents used coal as primary fuel in the winter. Coal was considered a higher-end fuel source for those with greater financial means. The natural gas burner use was another increasingly common higher-end fuel source and was also more prevalent in sedentary homes. Three of the five sedentary home residents used a gas burner for cooking, compared to just one in the tents. While stoves were used for heating and cooking, the gas burners were only used for cooking—usually quick cooking tasks, such as reheating food or boiling water. Residents in all four tents indicated their preference to use another fuel source, especially coal, while none of the residents in sedentary homes said the same. This result is similar to the finding of Xiao et al. (2015), where natural gas was only used in households with almost twice the median annual income in Nam Co.

Table 1 Particulate matter ($PM_{2.5}$) and black carbon (BC) measurements across all study sites

Mesurement site (*N*)		Avg[BC][a] (μg/m^3)	Avg[$PM_{2.5}$][a] (μg/m^3)	[BC][a]:[$PM_{2.5}$][a] (%)	Max [$PM_{2.5}$] (μg/m^3)
Tents (11)		13.0	2286	0.6%	157,000
Tarp tent (7)		11.5	755	1.5%	11,700
	only yak dung (5)	11.2	637	1.8%	11,700
	yak dung + gas (2)	12.0	1052	1.1%	10,500
Yak-hair tent (4)	*only yak dung*	15.8	4964	0.3%	157,000
Sedentary Homes (9)		6.9	509	1.4%	11,300
	only yak dung (5)	8.4	482	1.7%	11,300
	yak dung + coal/or gas	5.1	543	0.9%	6850
Other (6)					
Prayer room (2)	*butter lamps + incense*	3.6	76	4.7%	617
School cafeteria (1)	*yak dung + coal*	1.8	55	3.3%	502
Teacher's kitchen (3)	*yak dung + coal*	15.6	880	1.8%	12,400
Ambient (2)		1.1	25	4.4%	400

[a]Based on entire measurement period

Table 2 Types of residences where HAP was measured: top left, yak hair tent; top right, tarp tent; bottom left, concrete sedentary home

Measurement Site		Max [$PM_{2.5}$] (μg/m^3)	Time and context of max measurements
Tents			
Tarp tent	*only yak dung*	11,700	20:00; fire is being stoked in preparation of heating tea; plastic iced tea bottle and yak dung are added to stove
	yak dung + gas	10,500	18:33; deep frying bread in oil using a skillet on a one-burner natural gas stove; stove is also burning very hot with yak dung
Yak-hair tent	*only yak dung*	157,000	14:49; rainy day, piece of canvas is covering the ceiling vent hole; adobe stove is covered with plastic to protect from rain, not being used; yak dung added to improved stove and tent fills with white smoke
Sedentary homes			
	only yak dung	11,300	16:40; fire is being made using yak dung and newspaper; stoked and extreme amount of smoke seeps out of the stove; door is open but smoke hangs in air
	yak dung + coal and/or gas	6850	17:18; yak dung is added to stove to heat tea; dinner ingredients are being prepped; a yak butter lamp is also burning
Other			
Prayer room	*butter lamps + incense*	617	19:28; no observations within temporal proximity of max reading, but 43 yak butter lamps and incense were burning
School cafeteria	*yak dung + coal*	502	18:28; dinner is being cooked
Teacher's kitchen	*yak dung + coal*	12,400	17:26; dinner is starting to get cooked; only yak dung in use at the moment; very smoky; door is open; at 17:28 the cook opens the window
Ambient		400	18:37; many homes are preparing dinner

It is important to note, however, that yak dung was often extolled as a good primary fuel source because it was free and easy to use. Some residents even stated that they wouldn't know how to start a fire with coal. One respondent said that yak dung was natural so it was better for cooking. Additionally, residents in two of the three sedentary homes with natural gas burners said that gas was used only to make lunch because it was fast.

Awareness of HAP was not related to the residence or the fuel types. Four residents—two from tents and two from the sedentary homes – indicated that they noticed smoke in the home at certain points in time. One of the sedentary home

Table 3 Results of the nine semi-structured interviews

	Tents (4)	Sedentary (5)
Demographics		
Avg # of residents	5 people	5 people
Children under 5 present	25%	40%
Resident(s) smoke cigarettes	25%	20%
Stoves		
Use improved stove	100%	100%
Use traditional stove	25%	0%
Stove used all day unconditionally	75%	0%
Avg age of improved stove	4.8 years	7.6 years
Avg time stovepipe has been used with improved stove	3.6 years	4.6 years
Fuels		
Yak dung is primary fuel in summer	100%	80%
Yak dung is primary fuel in winter	100%	60%
Coal is primary fuel in summer	0%	20%
Coal is primary fuel in winter	0%	40%
Coal is secondary fuel anytime	25%	60%
Natural gas burner used for cooking	25%	60%
Would prefer to use another fuel source	100%	0%
Said yak dung is good because…		
it's free	50%	40%
it's easy to burn	50%	60%
it's natural	25%	0%
Said coal is good because…		
it burns hotter	0%	60%
it burns longer	50%	40%
Said gas burner is good because it's fast	0	40%
Smoke and health		
Notice the smoke anytime	50%	40%
Has health concerns related to stove use	25%	0%
One or more resident(s) has chronic health problem(s)	50%	80%

residents was aware that the room becomes smoky when the stovepipe was clogged. However, it was only the residents of a yak hair tent that had any health concerns related to the stove use. Two of the residents in tents and four of the residents in sedentary homes reported chronic health problems in the home, with hypertension, backaches and stomach issues being the most common, but they did not link them to the HAP. Based on Xiao et al. (2015), one possible hypothesis was that most residents were aware of the serious HAP problem and as they obtained the financial means, they would purchase alternative fuel and live in sedentary homes to reduce HAP and consequently its health impacts. However, the awareness of HAP in Golog was much lower than in Nam Co, and the concern on their health impacts was almost non-existent.

Ethnographic Participant-Observation

The sense of home

Nomadic and sedentary lifestyles are hardly a simple dichotomy and the residents' awareness of HAP and its impacts are also not at all simply related to the two lifestyles. Up until the late 1990s, most nomads lived in black woven yak hair tents. In yak hair tents, there is an opening in the ceiling of the tent for ventilation and residents have an open fire using an iron ring or a homemade adobe mud stove. The yak hair tent in this study was 30 years old, after having taken 3-4 years to make it. Today, these yak hair tents are few and far between in Golog as most nomads have transitioned to store-bought white plastic tarp tents, which are largely preferred because they are lighter, more waterproof and easier to setup. Tarp tent residents utilize cast iron improved stoves with stovepipes that vent the smoke through the ceiling of the tents. The yak hair tents are not seen by Tibetans as a mark of poverty or 'backwardness' but rather are viewed with a deferential respect as a symbol of the commitment to a 'traditional' Tibetan lifestyle. While the residents in the yak hair tent in the study expressed a great deal of pride in their home, they persist in using it because religious leaders say it is the right way to live and the 'traditional' ways must be maintained. The matriarch said that "development" is good, but not when it causes nomads to give up their livestock and tents. However, the conflicting desire was also visible when the patriarch expressed his desire to give up the yak herd and move into town.

It is important to note that this particular yak hair tent did not simply use an adobe stove but also had an improved stove when the residents were trying their best to maintain the traditional lifestyle. It is also important that it was only the residents of this yak hair tent who expressed an awareness of HAP in the region. They said that smoke from the improved stove was harmful to the eyes and other parts of the body, although smoke from the adobe stove was beneficial. The matriarch went as far to say that if there was no smoke in the yak hair tent, it was not good. Her reasoning was because the yaks ate herbal grasses. Her statement highlights the contradicting perceptions of the Tibetan residents towards HAP as they burn yak dung in both traditional and improved stoves. It is possible that other residents did not mention HAP because they considered the smoke from yak dung burning to be still beneficial, although they moved from traditional yak hair tents to tarp tents and used only improved stoves.

The matriarch's contradicting remark was also potentially possible due to the structure of the improved stove. The improved stove had a stovepipe, and yet the stovepipe terminus was kept within the yak hair tent. If the stovepipe were sent through the ventilation gap (which ran across the length of the tent's ceiling), it would prevent the residents from sliding a piece of canvas over the ventilation gap when it rains. Incidentally, this is exactly what caused the extreme instantaneous maximum $PM_{2.5}$ concentration of the whole study: 157,000 μg/m^3. A rainy day, the residents of the yak hair tent covered the ventilation gap with canvas and covered the adobe stove with plastic to protect it from leaks. The improved stove was used but had no direct ventilation except small gaps between the canvas and the tent, as well as the tent flap door when open (though the open tent flap sometimes caused the smoke to swirl without escaping). This highlights the importance of reconsidering what is considered "improved" in the Tibetan context.

The complex mixture of nomadic and sedentary lifestyles was also found in other ways. Four out of the five sedentary home interviews occurred with townspeople, but one occurred with nomads who have a 'sedentary' home on their pasture. It is increasingly common for: (a) individual nomad families to have a non-tent home built on their winter pasturelands; or (b) for the leader of a nomadic clan to have a non-tent home built on each of the seasonal pasturelands. The field researcher encountered both cases. For the former, the yak hair tent was pitched on the family's summer pastureland, but their concrete winter home was nearby (due to the micro-climate, this family only needed a summer and winter pasture and did not need to travel far between the two). In the latter case, at the summer pasture of a nomadic clan, the leader lived in a small concrete home while the other families and hired herders lived in surrounding tarp tents. Though nomadic by profession, the leader's concrete home was categorized as a sedentary residence due to its structural likeness to sedentary homes in town.

The fuels at play

Yak dung was by far the dominant fuel used in this study. For nomads, yak dung is a free and constantly available resource.[4] There are several ways in which the dung is dried. Clumps of fresh dung may be piled on the grass and then spread in a thin layer. Without precipitation for a few days, the layer will dry and can then be picked up in brittle pieces and added to a pile beside the home. Alternatively, fresh dung may be formed into corral-type wall around the home. Fresh dung can be slapped onto the outer walls of the home in order to dry beneath the eaves. Dry dung chips from the pastures may also be collected and piled up. Large plastic tarps are used to cover the dry dung pile to keep it out of the rain. If dung is being harvested from a corral wall, the plastic sheet will be kept over the section that's being harvested and then gradually moved along the wall. Often a large bin is kept inside the home to store a few hours' worth of dung brought in from outside. Townspeople could find plenty of yak dung in the surrounding fields, but they are more likely to buy sacks of dried yak dung. Occasionally, but not often, yak dung could be heard loudly popping during combustion, indicating that the dung chips had retained moisture. Xiao et al. (2015) have suggested that higher dung moisture inhibits complete combustion and leads to higher emissions, with less BC/$PM_{2.5}$ ratio. Indeed, smokier conditions tended to correspond with the popping.

The initial lighting of the stove often created some of the smokiest conditions in the home. Yak dung was the preferred fuel for starting fires. Some homes used a store-bought sleeve of wax to assist with fire starting. Others used wads of paper. If coal was used as a supplemental fuel source, it was added after the dung fire was lit. Coal was considered difficult to light from scratch but when added to an existing fire, it was said to burn hotter and longer than yak dung. All of the coal seen in this study was a dull and soft variety, indicative of bituminous nature. Other than in the school cafeteria, the impact of coal on HAP is hard to see (Tables 1 and 2) and that is most likely due to the prevalence of yak dung and also the inefficiency of the coal used in Tibetan households.

An unexpected 'fuel' burned at every study site was trash. Plastic drink bottles, plastic food wrappers, aluminum cans, and other miscellaneous rubbish were all seen being put into the stoves. In fact, the bins or buckets that store the yak dung or coal inside the home often doubled as trashcans—everything inside had the same destination. When asked, residents did not seem concerned about trash burning. However, on one occasion a young woman preparing to light the stove at a sedentary home was observed first removing several pieces of trash that her father had earlier put into the combustion chamber. She took the trash to an overflowing dumpster in the street and then proceeded to build the fire with yak dung.

Lastly, it is worth noting that all residences had electricity in the home. The townspeople were connected to an electrical grid, and the nomads had solar panels connected to charging stations. The Chinese government has subsidized these photovoltaic systems. Nomads use the electricity mostly to keep their smartphones charged and power a single light bulb at night. One tent even had a satellite television set.

Problems in perspective

At several instances when talking about HAP, climate change came up in conversation with nomads in the

[4] In one tarp tent, sheep dung was once mixed with yak dung in the stove. This is an uncommon practice.

foothills of Amnye Machin, a 6282 m snowcapped mountain revered by Amdo Tibetans. Some of these nomads, but not all, knew about 'climate change' as a global phenomenon. Yet whether or not it was known in a global context, all described local climatic changes. The consensus is that winters are getting longer and warmer, and summers are getting wetter with poorer grass. Amnye Machin's year-round snowpack is also seen to be getting smaller and more brittle year after year. Two nomads claimed to have seen large calvings recently. One said the snowpack began dwindling ever since the road construction began in recent years. The pavement factory—which sits 100 m from his tent—is a sign of "development" which is "good," but he also said it creates problems for animals and people and reduces the quality of the grassland. When asked what would happen if Amnye Machin were to completely lose his snowpack, another nomad said it would mark the end of the world.

In addition to climate change, ambient air pollution in Chinese cities was also well-known to all study participants in multiple conversations about HAP. Many were however surprised to learn that the air quality in their home could be worse than the notorious air quality of Beijing, confirming the low awareness of HAP in the region. The facemasks that are worn by almost all pedestrians in Chinese cities on smoggy days are also becoming ubiquitous in Golog, but not for the expected reasons. Tibetan townspeople and nomads, especially women, are wearing these masks outside to protect their nose and cheeks from the high-altitude sun and wind. The multicolored masks with printed designs or messages (in English or Tibetan script) are also treated like a fashion accessory.

Discussion

Building on the emerging Tibetan indoor air quality literature, our study is notable, because it is the first to work with Tibetan populations outside of the TAR. Because reference to "Tibet" within China most often refers strictly to the provincial TAR, many may be unaware that significant Tibetan populations live outside of "Tibet." These populations in the Qinghai, Sichuan, Yunnan, and Gansu provinces are more varied due to their locations in central China, but they are no less Tibetan.

All of the previous studies concluded that Tibetans are being exposed to very hazardous levels of PM, carbon monoxide and trace elements. Our findings affirm their conclusions. We found the air quality in sedentary homes to have roughly 75% less $PM_{2.5}$ and 50% less BC compared to tents. However, both sedentary homes and tents have average $PM_{2.5}$ concentrations over the time period that we measured that exceed WHO's daily average $PM_{2.5}$ air quality guideline by 20 and 90 times, respectively.

There are of course a few shortcomings of our study. This study was carried out in the summer months when the weather was most favorable. It is expected that our results do not portray the winter reality when Golog is perennially snowed-in and difficult to reach. In our previous measurements in Nam Co, Tibet, we found higher $PM_{2.5}$ concentrations in the spring than in the summer (Xiao et al. 2015) and we believe it will be even higher in winter. Also, due to logistical and instrumentation constraints, we were unable to record measurements for longer than 4–5 h at a time. Therefore, we were unable to convey 24-h average $PM_{2.5}$ concentrations. Finally, the extreme smokiness measured in the yak hair tent on one of the final measurement days caused the DustTrak and microAeth to malfunction. After the event, the DustTrak failed to fully zero-calibrate for the final three measurements and the microAeth reported a filter error in the middle of the final measurement day. Despite these errors, the data do not appear abnormal and were retained.

Rather than simply restate that the air quality inside Tibetan homes is extremely polluted and hazardous to health, we would like to discuss the ways in which this study could be used to inform current and future 'interventions' planned for the region. The WHO has characterized HAP as the world's top environmental health risk and 2014–2024 has been declared the UN's Decade of Sustainable Energy for All. This has attracted attention but context-specific knowledge is critical to building successful interventions 'in the field.' The context of Tibetan HAP is no exception. Previous Tibetan HAP studies have offered advice such as replacing yak dung, changing people's lifestyles, and introducing improved stoves, but such advice belies the complexity.

First and foremost, the voices of Tibetan people need to be better heard in the discourse about the air quality in their households. This is especially important in a global health and development sector that tends to esteem donors' concerns above beneficiaries' (Biehl and Petryna, 2013). It is clear that there are many entities interested in solving the problem of HAP in Tibet. The Chinese government, the World Bank, and the Global Alliance for Clean Cookstoves (a public-private partnership hosted by the UN) are involved. Small non-profits such as One Earth Designs (www.oneearthdesigns.org) are working on small-scale interventions. Plus, researchers in China have released studies describing the current energy-use landscape across Tibet and future directions that could be taken towards the sustainable development of wind and solar power (Ping et al. 2011, Wang, Qiu 2009). We need to have a better understanding of what type of improved cookstoves would actually work as an intervention strategy in Tibet, especially when the existing improved cookstoves do not seem to have any significant impact on HAP in Golog.

It is important to note that the vast majority of study participants were not concerned about their indoor air quality. Xiao et al. (2015) have suggested that Tibetan nomads were more concerned about health impacts related to stove use than our study. There is a possibility that those results were influenced by a social desirability bias. In order to mitigate this issue, our study worked to use interviews and questions characterized by greater neutrality. On the other hand, it is very possible that distinct Tibetan populations perceive HAP-related risks differently. Still, in the face of such uncertainty about the biological gradient and exposure-disease causality, we must acknowledge that HAP more often than not is an insidious risk. Accretional in nature and attritional in effect, HAP can be normalized for the chronically exposed and therefore not perceived to be problematic (Mobarak et al. 2012). Nixon (2011) has usefully termed such environmental risks to be examples of "slow violence," which he describes to be "a violence that occurs gradually and out of sight…dispersed across time and space." Recognizing HAP in this way may be the best explanation as to why the majority of participants in this study fail to perceive any health problems associated with their combustion practices. Making the residents become more aware of this problem by changing their perception of this environmental risk is therefore potentially the most important path forward in mitigating the HAP. We might start by trying to understand the perception that smoke from yak dung burning is beneficial.

The concern among Tibetans about local climate change deserves greater attention. Nomads in this study were drawing conclusions that are corroborated by recent studies—climate change in Tibet is causing a shorter summer growing season and poorer grassland quality (Yu et al. 2012, Klein et al. 2007, Yu et al. 2010). Further corroborating our ethnographic findings, a 2009 survey performed in a different TAP revealed "health problems" to be the most commonly cited consequence of climate change for "people and quality of life," while "less snow" was the most commonly cited consequence for "sacred mountains" (Byg, Salick 2009). If Tibetans see climate change—not HAP—as a major cause for concern this warrants the attention of scientists and development practitioners. Most important might be to enhance the residents' awareness of the potential impacts their yak dung burning could have on glaciers and link HAP to both health and climate change issues.

This study has revealed two novel realities about Tibetan HAP—the first rooted in tradition; the other an unfortunate mark of modernity. The measurements from the prayer room suggest that even if air quality is mitigated from heating/cooking sources, there is yet another potential and non-negligible source of air pollution. Because yak butter lamps are burned frequently and for long durations, this source cannot be ignored. Tibetans can now buy plastic battery-powered flickering 'butter lamps'—this may or may not be a solution to the HAP issue, but it does relate to the second novel reality uncovered by this study. Indoor trash burning is a prevalent practice across all household types now that packaged consumer goods are accessible. A study on solid waste management in urban areas of the TAR concluded that lack of infrastructure and regulation was a major cause for concern but made no mention of indoor trash combustion (Jiang et al. 2009). Little research has been done on household trash burning, but a study from Ghana linked the practice with low birthweight (Amegah et al. 2012). A global assessment of *open* burning of domestic waste found that China burns more residential waste than any other country (Wiedinmyer et al. 2014). Any HAP intervention should understand that Tibetans are consuming/creating more trash, but they do not have access to adequate waste management infrastructure. If it does not get burned, trash often ends up littering the grasslands and streams.

A more nuanced characterization of exposures is useful to gain greater discernment about the extent of exposures. Previous studies have identified women and children as the most exposed members of the Tibetan home, but the family unit is not the only denominator for indoor air pollution. For example, the social dynamic of hired herders who live in stove-less satellite tents is a notable detail that changes the characterization and nature of the HAP exposure. From a distance, hired herders look like part of the family, but they spend less time in the cooking tents and technically the 'household' air pollution is an occupational exposure for them, in certain respects. In addition, the measurements from the cafeteria kitchen and the teachers' kitchen also provide a limited glimpse into different types of exposures. Absent more rigorous exposure science testing, this nuanced breakdown helps to avoid exposure misclassification when extrapolating average measurements to the potentially exposed.

The combustion of yak dung for heating and cooking is certainly an interesting aspect of Tibetan culture. However, no study participants claimed to use yak dung for cultural reasons or out of respect to ancestral traditions. Rather, participants prized it for being free, easy to burn, or natural. Additionally, all of the nomadic tents said they would prefer to use an alternative fuel source other than yak dung. Even the matriarch of the yak hair tent—who spoke of the importance of preserving the old tent and nomadic way of life—said she would prefer to use coal if it could be provided for free. Such evidence leads us to believe that economics and convenience/comfort are first and foremost preserving yak dung as the primary household fuel. Furthermore, the notion of 'development' is also problematic in light of our study. 'Development' is a term that Tibetans use with favorable connotations (Ljunggren et al. 2010), but our findings suggest it's often used with conditions. We commonly heard the phrase that "development is good, but…" All stakeholders need to engage in a deeper dialogue to understand each other's definition of 'development.'

If Tibetans are talking primarily about *economic* development such that everyone can afford to build sedentary homes on their pastures and buy coal from the market, the HAP problem would not be solved. Similarly, if improved cookstoves only work well in the laboratories, then the HAP problem would not be solved either. There needs an enhanced awareness of the HAP problem among the Tibetan population, a better linkage between HAP and climate change, and a better dialogue among the stakeholders and the residents in Tibet for obtaining better indoor air quality in the region.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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