BioscienceHorizons Volume 11 2018 10.1093/biohorizons/hzy014

Research article

Firewood usage and indoor air pollution from traditional cooking fires in Gazi Bay, Kenya

Julia Jung* **and Mark Huxham**

School of Applied Sciences, Edinburgh Napier University, Sighthill Campus, 9 Sighthill Ct, Edinburgh EH11 4BN, UK

***Corresponding author:** School of Applied Sciences, Edinburgh Napier University, Sighthill Campus, 9 Sighthill Ct, Edinburgh EH11 4BN, UK. Email: 40178829@live.napier.ac.uk; JJEduOcean@gmail.com

Supervisor: Prof. Mark Huxham; School of Applied Sciences, Edinburgh Napier University, Sighthill Campus, 9 Sighthill Ct, Edinburgh EH11 4BN, UK.

Mangroves are increasingly being recognised for the important ecosystem services they provide, including carbon fixation, shoreline protection and fisheries habitats. In addition, they provide typical forest goods such as timber and firewood; harvesting these can cause forest degradation and loss. In Kenya, a large proportion of the rural population cook using firewood on traditional, inefficient three-stone fires. Although harvesting mangrove wood is illegal, the high poverty rate, absence of alternative fuels and lack of law enforcement mean it is likely to remain widespread, with consequent pressure on the forests. The use of three-stone fires has been associated with high levels of indoor air pollution, causing adverse health impacts. The current project aimed to determine a baseline of wood usage and health burden caused by indoor air pollution at a mangrove dependent community in Gazi Bay, southern Kenya. Basic information about fuel usage and perceived health problems related to indoor air pollution was collected using a questionnaire. Wood usage patterns were recorded for 28 days to establish the average daily wood consumption and main species used. Passive diffusion tubes were used to assess CO concentrations over 24 hours. Particulate pollution for the size fraction PM2.5 was measured during cooking using a DustTrak aerosol monitor. Mean daily per capita wood consumption was 1.2 kg although this varied significantly depending on household size, with larger households using less per capita wood. The mangrove *Rhizophora mucronata* made up 10% of wood used and people spent, on average, 22 hours per month collecting wood. The mean 24-hour CO concentration was 5.9ppm. The average level of PM2.5 during cooking was 10 mg/m^3 respectively. Chronic exposure at those levels is expected to cause significant health impacts of the kinds indicated by symptoms reported from the questionnaires. Improved cookstove introduction in Gazi is recommended as feasible as participants showed not only interest in improved cookstoves and awareness of the health implications from indoor air pollution, but also were willing to invest financially in improved cookstoves.

Key words: biomass fuel use, air pollution, improved cookstoves, mangroves, carbon monoxide, particulate matter

Submitted on 31 May 2018; editorial decision on 28 November 2018

Introduction

Mangroves are tidal forests growing in the tropics and subtropics, which provide important cultural, regulatory and provisioning ecosystem services (Locatelli *et al.*, 2014). These include nursery habitat provision for fish and crustaceans, protection from natural hazards including storms and coastal erosion (Jardine and Siikamäki, 2014), and regulation of water quality by filtering pollutants (Ouyang and Guo, 2016). Because they can assimilate large amounts of carbon in their sediments, they are important in mitigating the effects of anthropogenic climate change (Siikamäki, Sanchirico, and

Jardine, 2012). Additionally, mangrove forests provide numerous goods to local communities, including food, timber, firewood and items used in traditional medicine (Kumar and Prashant, 2014).

Mangrove forests show high resilience to natural threats such as storms, fire and disease. However, they are amongst the fastest disappearing ecosystems worldwide as sea level rise, land-use change and deforestation have led to annual loss rates of 1–2% (Locatelli *et al.*, 2014; Miteva, Murray, and Pattanayak, 2015). Loss of forest leads to loss or diminution of the services it provides; for instance carbon stored below-ground is vulnerable to release, with land-use change potentially leading to rapid oxidation of carbon in mangrove sediments (Pendleton *et al.*, 2012).

Published rates of loss only count complete forest canopy removal and do not include cryptic damage caused by forest degrading activities such as firewood extraction (Huxham *et al.*, 2015). This is important as wood is still a crucial biofuel for many households in sub-Saharan African, which use firewood on a daily basis (Jagger and Jumbe, 2016). In rural Kenya for example, it is the main cooking fuel for 68% of the population (Ochieng, Tonne, and Vardoulakis, 2013).

Along the Kenyan coast, human settlements are contiguous with the main mangrove areas, which are therefore commonly used for firewood extraction (Huxham *et al.*, 2015). Many of these rural households still use traditional cooking methods such as the three-stone fire. These have very low efficiency levels, and therefore require large amounts of fuelwood (Ochieng, Tonne, Vardoulakis, 2013). The use of inefficient three-stone fires also has social implications including higher physical burdens and opportunity costs, since more time is spent collecting firewood. This is especially important as it limits women and children from improving their education or spending time on income-generating activities (OECD/IEA, 2006).

Another concern about the use of three-stone fires is that the smoke produced creates high levels of indoor air pollution. Each year, this contributes to around 4 million premature deaths globally (Lambe *et al.*, 2015). Respiratory symptoms including dry cough, phlegm production and breathing difficulties are the most commonly reported. However, other health issues such as back pain, cardiovascular disease, cancer, blindness and low birth rates have also been linked to indoor air pollution (Quansah *et al.*, 2017). The amount and composition of indoor air pollution varies depending on many factors including fuel size and moisture content (Bhattacharya, Albina, and Myint Khaing, 2002). Some of the most common and harmful components are suspended particulate matter and carbon monoxide (CO), which both cause adverse health impacts through acute or chronic exposure above certain thresholds (WHO, 2006; Mondal and Chakraborty, 2015). Fine particulate matter, which consists of particles up to 2.5μm (PM2.5), is the most commonly measured component of suspended particulate matter as it has been shown to cause serious health impacts (Badamassi, Xu, and Leyla, 2017). This is because it can easily bind toxic metals or carcinogenic compounds, and its deposition occurs deep in the alveolar lung tissue, where it can remain for prolonged time periods (Li *et al.*, 2017a, 2017b). For CO, the main adverse health effects are due to hypoxia. CO competes with O_2 for haemoglobin molecules by forming carboxyhaemoglobin, which prevents the release of haemoglobin and thereby causes hypoxia (WHO, 2010).

In addition to their adverse health impacts, suspended particulate matter and CO also accelerate anthropogenic climate change (Jagger and Jumbe, 2016). This is because suspended particulate matter in the atmosphere can absorb and scatter solar radiation (Li *et al.*, 2017a, 2017b). CO is an important greenhouse gas, as it has a 20-year Global Warming Potential of 2-6, higher than the equivalent for CO_2 which has a 20-year Global Warming Potential of 1. This is especially important since CO remains longer in the atmosphere than CO_2 as it is not fixed though plant assimilation (Bailis, Ezzati, Kammen, 2003).

The introduction of improved cookstoves in rural communities has long been advocated to reduce deforestation, lessen the adverse health effects from smoke pollution, decrease greenhouse gas emissions, and reduce the negative social impacts from firewood collection. Within the last 40 years, there have been many attempts to introduce improved cookstoves in a range of low and middle income countries (Quansah *et al.*, 2017). Many such projects have not been successful in achieving long-term adoption rates and significant reductions in the parameters mentioned above due to a variety of reasons not yet fully understood (Gall *et al.*, 2013). However, full consideration of the local cultural and socio-economic context, including the willingness to accept the improved cookstoves and the establishment of a suitable cookstove model that balances cheap and efficient technology have been suggested as pivotal aspects (Foell *et al.*, 2011; Lambe *et al.*, 2015).

Study site

This study was conducted in Gazi Bay (4°25′S and 39°50′E), located 55 km south of Mombasa. The mangrove forest here covers an area of 600 ha and is the most studied mangrove forest in Kenya (Kairo, Wanjiru, and Ochiewo, 2011). There are two villages adjacent to the mangrove, Gazi and Makongeni, consisting of around 600 and 300 households respectively. Most households rely on multiple livelihood activities including fishing, palm leave weaving and farming (Ochiewo *et al.*, 2017). This subsistence lifestyle and the high poverty rate of the coastal region causes a high dependency on primary natural resources including firewood. Firewood extraction has been identified as one of the leading causes of mangrove degradation (Government of Kenya, 2017). There has been some controversy around sustainable harvesting laws in Gazi Bay. Previously, each villager could buy a permit from Kenya Forest Service for KSh100 per month, which allowed them to collect one bundle of mangrove fuelwood per day. However, it was thought that this fee could be too expensive for poorer households, who might collect firewood illegally (Kairo, Wanjiru, and Ochiewo, 2011), as confirmed by surveys conducted in 2015 (Huxham *et al.*, 2015). Currently, there is no legal mechanism to collect mangrove firewood (F. Munyi, personal communication). However, a recent government report shows that most villagers are not aware of this change in law. Therefore, the continued use of mangrove firewood in Gazi Bay is highly likely (Ochiewo *et al.*, 2017).

Aims and objectives

The aims were to examine current patterns of fuelwood collection and use in Gazi Bay and to explore possible social and health impacts of the use of three-stone fires for the local population, as part of a larger project aiming to introduce improved cookstoves to Gazi Bay. Objectives of this research were to:

- Determine a baseline of the current daily amount of used fuelwood and the species of wood most commonly used in Gazi Bay.
- Describe the physical burden and opportunity costs of firewood collection to gain an understanding of the potential social implications of firewood collection.
- Determine a baseline of current indoor air pollution levels caused by CO and PM2.5 including the presence of spatial differences in pollution levels within households.

Outcomes from this baseline study will be used to test the efficiency of the improved cookstove introduction.

Methods

Questionnaire

A semi-structured questionnaire (Supplemental data) was conducted with 180 households, and 28 of these were selected as 'monitored' for participation in the full study (Bailis and Edwards, 2007). This was organised by Kenya Marine and Fisheries Research Institute (KMFRI) MSc student Agnes Mukami and carried out by KMFRI students and interns with the help of local translators. Each pair of KMFRI student and local translator started at a different haphazard point in the two villages but sampled households systematically by conducting a questionnaire with every second house from that starting point onwards. Selection of monitored households was made on the basis of the following criteria adapted from Ochieng, Tonne, and Vardoulakis (2013):

- Functional homestead (at least mother and children present),
- Cook daily in designated cooking area in home,
- Use firewood as main fuel on a daily basis,
- Firewood is either bought or collected in fixed bundles on a regular basis,
- Want to participate in pilot study and show interest in improved cookstoves,
- Do not sell food for a business.

Subsamples of the questionnaire were analysed to describe the primary cooks' experiences of the firewood collection and cooking process.

Wood diary

In order to establish the mean per capita wood use over 24 hours, 'wood diaries' were used as an adapted version of the kitchen performance test (Bailis and Edwards, 2007). Daily wood measurements were taken from the 13 February 2018 until the 13 March 2018 in the selected households. Measurements were taken by 5 local 'wood observers' who were able to identify the different species of firewood commonly used. Each household was assigned to one of the wood observers, who conducted the wood measurements at the same time each day. The wood was tied in one or more bundles and weighed as shown in Fig. 1. Households were instructed to only use wood from the weighed pile that day and store any newly collected wood on a separate pile to be weighed the next day (Benjaminsen, 1997). Digital luggage scales with a maximum capacity of 50 kg were used to weigh the wood. The scales were calibrated with a national standard traceable mass of 200 g using a Sartorius CPA16001S scale prior to the fieldwork. They showed a bandwidth of accuracy of ±7 g.

Indoor air pollution

Carbon monoxide

Gastec Detector tubes, with a range of 0.4–200ppm, were used to measure the levels of CO in 25 households (rather than all 28, due to a limited number of available Gastec tubes). CO levels are measured by the passive diffusion of CO into the tubes, which causes a colour change through reaction with the reagent inside. Total CO concentrations over 24 hours were recorded. A conservative approach was adopted for interpreting the visual scale as the lower concentration was recorded if the colour change was between two concentrations on the visual scale (J. Currie, personal communication). Total concentrations were then converted to average 24-hour concentrations using the following equation as recommended by the manufacturer (Gastec, 2017):

$$\text{Average Concentration} = \frac{\text{Dosi} - \text{Tube Reading}(\text{ppm})}{\text{Sampling Time}(\text{hours})}$$

Two tubes were placed in each household, one tube on the wall closest to the fire, and one on the opposite wall away from the three-stone fire (Fig. 2). They were installed for the maximum sampling time of 24 hours. To establish the ambient air pollution levels, two tubes were also placed outside in

Figure 1. 'Wood observers' weighing bundles of firewood for the daily wood measurements.

Figure 2. Sampling setup for CO passive diffusion tubes. Red circles indicate location of Dosi tubes, and the yellow circle shows the three-stone fire.

each village, away from any apparent smoke pollution at the same time, as shown in Fig. 3.

Particulate pollution

A DustTrak aerosol monitor model 8520 was used to measure the amount of particulate pollution in each household while cooking for 15 minutes. This uses a laser diode sensor to measure light scattering from particles in the size fractions from 0.1 to 10μm and has a range of 0.001–150 mg/m^3. The aerosol monitor was placed in the combustion zone, within 1 m of the stove edge and with the inlet mounted at a height of around 1 m, to correspond with the breathing height of the primary cook (Fig. 4). The time interval for data points was set to 1 minute and the flow rate to 1.7 l/min (CEIHD and Gaia Association, 2007). Representative ambient samples were taken throughout the sampling period for 15 to 30 minutes, at different times of day and locations throughout the two villages, away from any home or obvious smoke pollution.

Figure 3. Sampling arrangement for the ambient CO measurements with the passive diffusion tubes. Red circles indicate the locations of the tubes.

Statistical analyses

Summary statistics on sources of wood, processes of wood gathering and cooking and reported impacts were derived from the questionnaire data. Data from monitored households were used to examine the effect of household size on average daily per capita wood consumption, using a regression analysis (with residuals examined for parametric assumptions and data transformed where necessary). A Wilcoxon signed-rank test was used to do a pairwise comparison of the CO levels close to and away from the fire within each household. Statistical tests were conducted using Minitab 17 and R software.

Results

Questionnaire

Methods of obtaining fuelwood

Most respondents, (62.6%) reported that their wood was all gathered by themselves or members of the household. Only

Figure 4. Sampling setup to measure particulate pollution during the cooking process in households.

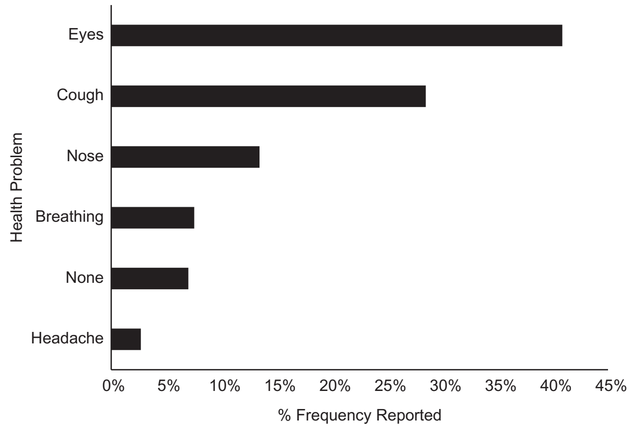

Figure 5. A summary of the main health problems or areas affected by smoke pollution ($n = 108$).

16.5% stated that their wood was 'all bought'. The average number of wood collection trips taken per month was 7.1 (95% CI = 1.8; $n = 53$). The average number of hours per trip was 3.1 (95% CI = 0.5; $n = 68$). Therefore, an average of 22 hours was spent collecting firewood per month by each household. The maximum number of hours spent on one trip was 10. Daily trips were the maximum frequency of trips recorded. The average distance per trip was 1.8 km (95% CI = 0.3; $n = 57$), and the maximum distance recorded was 6 km. The most frequently used methods to gather firewood were breaking dead branches off trees, used by 42.2% of all respondents, and picking up dead branches from the ground, reported by 36.7% of respondents. Some respondents (7.4%) also mentioned cutting down trees when collecting firewood. In most households, 75.5%, the mother was the primary wood collector. However, children were the primary wood collector for 19.2% of the households.

Cooking process

The three-stone fire was the most commonly used cooking appliance, used by 92% of households. Only 8% of households used stoves ($n = 96$). In terms of cooking arrangements, 38.8% of households cooked in an outside shed. The second most frequent arrangement (32%) was using a separate room inside. However, 20.4% of the households had a cooking area in the living/sleeping room. Firewood including coconut was by far the most frequently used main fuel, reported by 75.7% of the households. Charcoal was the second most frequently reported main fuel, used by 15% of the households. Less than 10% of the households stated using paraffin, electricity or gas as their main fuel.

Cooking experience for the primary cook

Smoke was mentioned most frequently (53%) as the most annoying aspect of the cooking process, followed by heat (25.9%) and the time spent cooking (11.9%). The most frequently mentioned health complaints caused by smoke were eye problems with 40.9%, and coughing (28.5%), followed by nasal irritation and overall breathing difficulties as illustrated by Fig. 5.

Attitudes towards improved cookstove introduction

Almost all households, 97.1%, stated interest in the improved cookstove ($n = 105$). The average payment they would be willing to make for an improved cookstove was KSh 494 (GBP 3.54; SD = 441.66; $n = 76$). The maximum amount that they would be willing to pay was KSh 2000 (GBP 14.32).

Wood diary

Species usage patterns

There were 40 different species used as firewood. Fig. 6 shows a summary of the species used and their percentage frequency usage. *Delonix regia* was the species used most frequently in 16.2% of the records. Overall, the average number of species recorded in each house per day was 1.7 (95% CI = 0.2; $n = 28$).

Drivers of variability of per capita wood consumption levels

The mean per capita (perCap) wood usage in Gazi Bay was 1.2 kg/day (95% CI = 0.1; $n = 400$). However, there was a significant negative relationship between average per capita daily wood consumption and household size (linear regression on log10 transformed data: log10 household size = −1.3 × log10 wood use + 1.02; $F = 15.95$, df = 1, 25, $p < 0.001$, adjusted $r^2 = 0.36$). Hence every increase of one person in household size led, on average, to a reduction in wood use of ~0.5 kg perCap (Fig. 7). The average household size was 7 (95% CI = 0.2; $n = 769$), but overall household size ranged

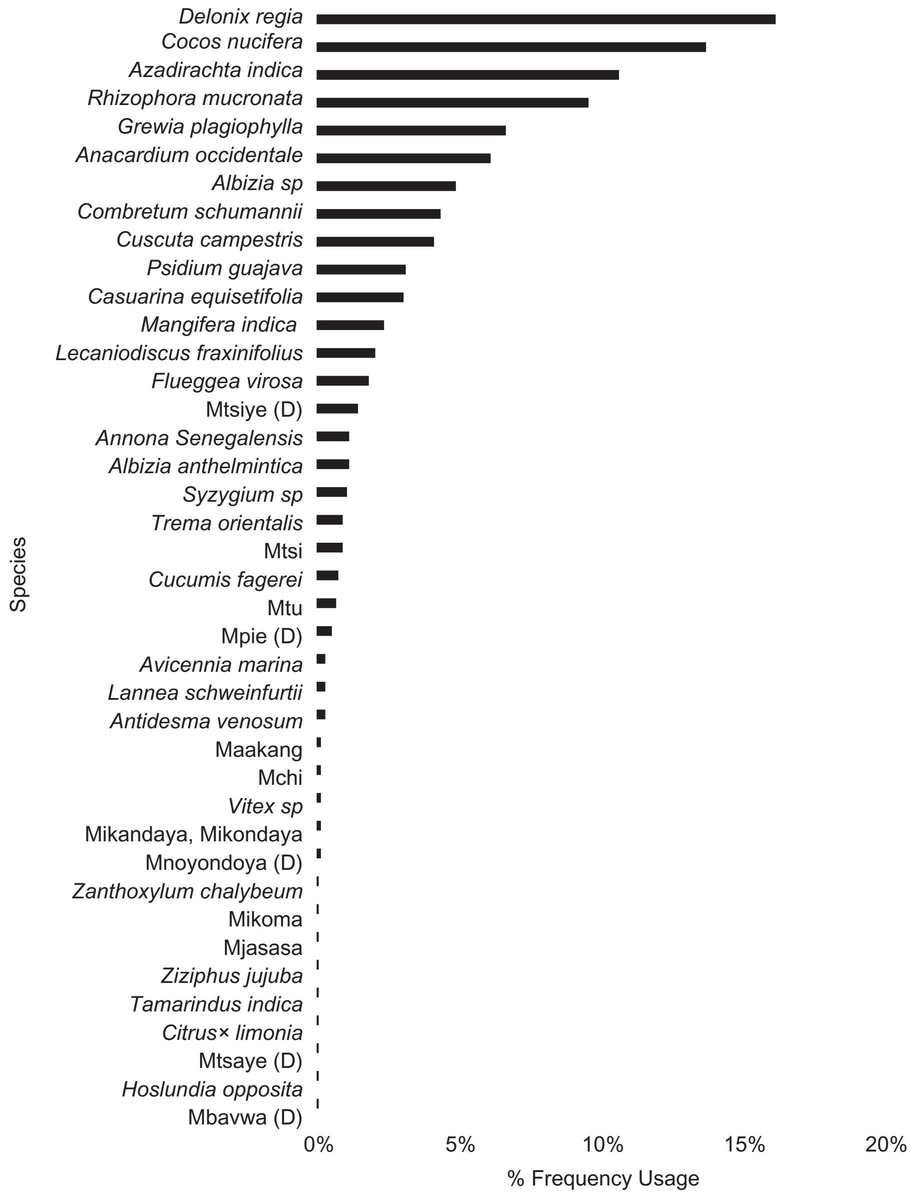

Figure 6. A summary of the percentage frequency usage of different species used for firewood (*n* = 1305). Non-italic names indicate the Swahili name, (D) indicates species, which could only be identified by their local Digo name.

from 2 up to 25 members. The household with the lowest average wood consumption of 0.21 kg perCap had on average nine members. The maximum average wood consumption per household was 2.82 kg perCap, recorded in a household with on average five members.

Fig. 8 shows the temporal variation of overall average 24-hour per capita wood usage throughout the sampling period. Values ranged from 0.6 kg/day/perCap recorded on 6 March 2018, up to 1.2 kg day/perCap recorded on 20 February 2018. However, there is also high variability in the 95% confidence intervals for each date.

Indoor air pollution

Table 1 shows a summary of total and average CO concentration over 24 hours for each sampling location and the overall concentration in the households. The median difference between samples from the two replicate locations was significantly different from zero (Wilcoxon signed-rank

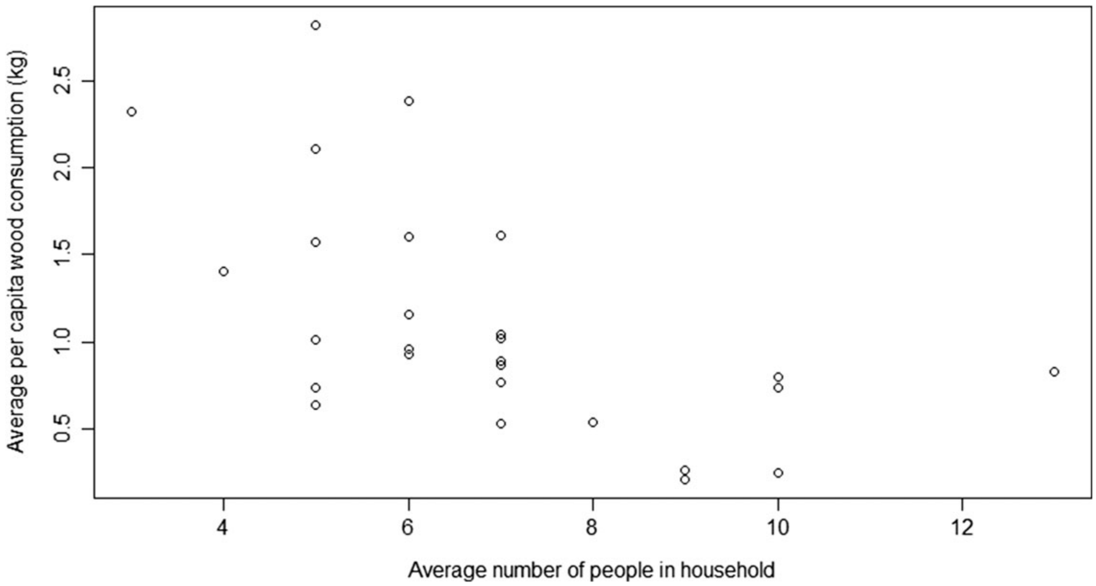

Figure 7. Household size (mean reported number of people) and mean per capita wood consumption for each household, showing a significant negative relationship ($n = 27$). Note that raw data are given here for clarity, but regression was performed on $\log_{10}$ transformed data.

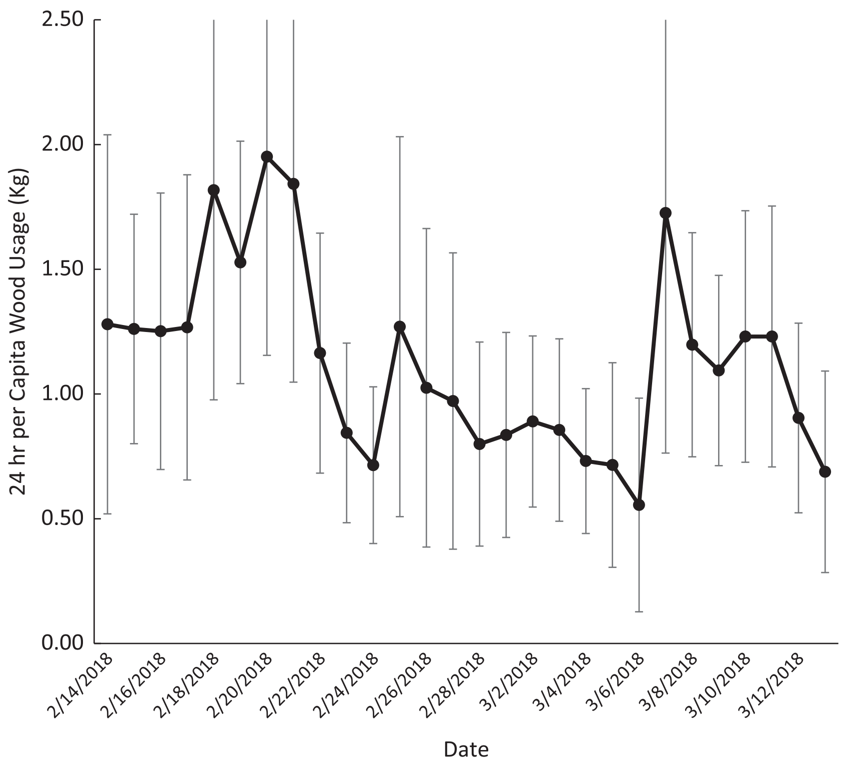

Figure 8. Temporal variation in mean (±95% CI) daily per capita wood usage throughout the sampling period.

test, $T = 94.0$, $n = 24$, $p = 0.01$). The maximum average value of PM2.5 was 73.9 mg/m^3 (95% CI = 19.8, $n = 29$). The average concentration of PM2.5 was 10 mg/m^3 (95% CI = 3.4, $n = 29$). The mean and maximum ambient PM2.5 concentrations were smaller than 0.1 mg/m^3 (95% CI < 0.1, $n = 22$).

Table 1. Summary of total and average CO concentration over 24 hours for each sampling location and overall in the households

Sampling location	Total 24-hour CO concentration (ppm)	95% CI of total 24-hour CO concentration	Sample size	Average 24-hour CO concentration (ppm)
Overall in household	141	+/− 19	50	5.9
Fire	166	+/− 21	25	6.9
Not fire	116	+/− 30	25	4.8
Ambient	10	-	4	0.4

Discussion

In common with much of rural Africa, there is a heavy reliance on wood in Gazi, with 75% of households using it as a primary fuel at an average consumption of 1.2 kg perCap/day. Women and children were responsible for wood collection in 95% of households, spending an estimated average of 22 hours per month on collection (although with individual trips of up to 10 hours duration). This suggests a considerable social and environmental burden, combined with a range of reported health impacts. The levels of CO and particulates recorded suggest long-term damage to health is likely.

Wood usage

Species usage patterns and destructive potential of wood collection process

The species used in this study have also been mentioned by similar studies evaluating fuelwood usage for Kenya's coastal zone (Kituyi *et al.*, 2001a, 2001b). *Cocos nucifera* was found to be a crucial species as not just the stem, but also the fronds and husks were some of the most commonly used fuels (Kituyi *et al.*, 2001b). *Delonix regia* was overall the most commonly used species in the present study but had not been mentioned in earlier studies. However, this could also be due to its occasional translation from Swahili as *Senna siamea* or as more generally 'ironwood' (Lim, 2014). Therefore, it is possible that the term refers to two or more species when used by the local community.

Whilst 40 species were reported as providing fuel, the four commonest provided more than 50% of the total. This pattern, of a few dominant species and a wide number of minor species used interchangeably, is typical in other relevant studies (Kituyi *et al.*, 2001a). This matches the reported harvesting methods, as the most commonly reported methods of breaking off dead branches or picking up dead wood from the ground indicate an opportunistic harvesting behaviour with the aim of getting dry wood rather than targeting only specific species. However, some households also reported cutting trees. While there are laws to avoid this, such as the recent 9- day ban on cutting trees throughout Kenya (J. Kairo, personal communication; Tobiko, 2018), there is a lack of enforcement, often caused through difficulties in communicating government laws to the local community (Kairu *et al.*, 2018). This is especially important regarding the use of mangrove firewood, as many villagers still believe it is legal to use with a permit from Kenya Forest Service (Ochiewo *et al.*, 2017), when in fact this permit is only applicable for terrestrial forests (F Munyi, personal communication). Two species of mangrove, *Rizophora mucronata* and *Avicennia marina*, were recorded as fuelwood, with *R. mucronata* constituting 10% of the records. *R. mucronata* is known as a preferred species for fuel due to its high calorific value (Government of Kenya, 2017).

Drivers of variations in per capita daily wood consumption

Household size caused significant variation in wood consumption, with increasing size leading to significantly lower per capita daily wood consumption. This phenomenon has been shown in other biomass fuel studies in rural Africa. For example Johnson and Bryden (2012) showed that as household size increases from 5 to up to 20 members, per capita energy consumption is almost halved, matching the reductions in per capita wood usage shown here.

In addition to large between-household variation, there was large temporal fluctuation in the wood usage data. These temporal changes may be seasonally influenced by commencement of the rainy season, as the first rains of the season (e.g. 21 February), caused some households to switch entirely to using alternative fuels for a few days. This has also been observed in other studies (Johnson and Bryden, 2012). These results emphasise the need for protracted studies that can capture temporal variation; clearly short snapshots of wood consumption could give very misleading figures. The extrapolated annual usage in Gazi Bay of 438 kg/year/perCap is similar to other recent studies in East Africa, which found the average usage to be 637 kg ± 229 kg/year/perCap (Stoppok *et al.*, 2018). Given a minimum estimated population size for Gazi Bay of 3486 (based on the 498 households reported in Huxham *et al.*, 2015, multiplied by an average of seven people per household reported here) this implies at least ~1, 528 tonnes of fuelwood is used in the area every year. Since this is nearly all derived from wild, local woodland it gives an indication of the degree of pressure fuelwood extraction is imposing.

Social burden of firewood usage

The social context of firewood collection reported here reflects the high poverty rate in Kenya's coastal region as most households gather their fuelwood rather than buying it (Kairo, Wanjiru, and Ochiewo, 2011). Other studies in East Africa have also reported numerous collecting trips per month, carried out by the mother or children, each lasting for a few hours and usually covering short distances of less than 2 km (Tabuti, Dhillion, and Lye, 2003). The implication for children involved in firewood collection is considerable as they were the primary firewood collectors for almost 20% of the households. Spending an average of 22 hours per month collecting firewood is likely to have a significant impact on educational opportunities, suggesting the significant social burden the use of three-stone fires has on the local community (Gold Standard, 2016).

Indoor air pollution

When incorporating differences in wood moisture content, fuelwood type, season, type of measurement and ventilation rate, which have all been shown to influence indoor air pollution levels significantly, results from this study are similar to those reported in the literature (Khatiwada, 2009; Klasen *et al.*, 2015; Ni *et al.*, 2016; Sidhu *et al.*, 2017; de la Sota *et al.*, 2018).

Effects of carbon monoxide

The current WHO 24-hour limit for CO is 6.11ppm to ensure COHb levels of 2% are not exceeded. This is because at this concentration, maximum exercise ability and time to angina are significantly reduced and chest pain, caused by reduced blood flow to the heart, is reported (WHO, 2010). The overall 24-hour CO concentration measured in the current study—5.9ppm—was lower than the WHO limit. However, the significant spatial variation within households is important as CO levels near the fire exceeded WHO guidelines by 0.79ppm. Additionally, acute CO levels are expected to cause significant health impacts due to the high short-term exposure during the smoldering phase, which is likely to exceed the short-term WHO guidelines of 87ppm over 15 minutes (WHO, 2010). Guidelines for chronic exposure to minimise health effects have been recommended to be around 4-5ppm. Therefore, even if short-term limits were not exceeded and COHb levels were lower than 2%, other adverse health outcomes are expected. This is supported by the symptoms of mild CO poisoning such as headache, breathing problems and chest pain reported here. However, those symptoms can also be caused by other types of indoor air pollution. Therefore, direct testing of COHb blood levels would allow for a stronger causal linkage to CO levels specifically (Mahoney *et al.*, 1993). This is especially important for the 20% of households cooking in their sleeping/living area as the family members from those households are exposed to those levels for even longer time periods.

Effects of particulate pollution

The WHO air quality guideline (AQG) for PM2.5 24-hour exposure is 0.025 mg/m^3. Above this level, total cardiopulmonary and lung cancer mortality have been shown to increase significantly with long-term exposure (WHO, 2006). The average PM2.5 concentration measured during cooking was 400 times the AQG value, thereby also exceeding the WHO Interim target 1 set at 0.23 mg/m^3 per minute for unvented stoves. Prolonged exposure to indoor air pollution above the level of Interim target 1 is associated with a 15% higher long-term mortality risk compared to the AQG (WHO, 2006). Therefore, significant increases in mortality due to indoor air pollution can be expected for the affected households.

The coughing, chest pain and breathing problems reported in this study are all symptoms of high-level particulate matter exposure, which has been shown to aggravate lung disease and decrease the strength of the body's immune system (Kim, Jahan, and Kabir, 2013). Additionally, increased blood coagulation and cardiovascular risk factors associated with stroke or heart rhythm disturbances are possible causes for the observed chest pain and increase mortality risk (Zhao *et al.*, 2017). Furthermore, the reported eye irritation can result in chronic eye damage, such as cataracts, caused by corneal cell death from prolonged PM2.5 exposure (Park *et al.*, 2017; Belkin, 2018). Similarly, PM2.5 has been shown to significantly alter the nasal microbial community structure, causing the commonly reported nasal irritation, which has been suggested to contribute to future disease development (Mariani *et al.*, 2018). However, more traceable medical outcomes could also be used here to establish a better link between particulate matter levels and indoor air pollution-related illness.

Feasibility of improved cookstove interventions

The fact that smoke was identified as the most annoying aspect of cooking by the primary cook and the numerous health problems mentioned in relation to the smoke indicate awareness about the health effects of indoor air pollution. This is important as creating awareness has been identified as a crucial step in facilitating improved cookstove adoption (Muller and Yan, 2018). Additionally, as the majority of households showed willingness to invest financially in an improved cookstove, the prospects seem propitious for such an introduction. However, the amount that households were willing to invest in an improved cookstove was relatively low compared to other studies (Van der Kroon, Brouwer, and Van Beukering, 2014). This highlights the importance of finding a design that balances efficient technology with cultural and economic desirability, to achieve widespred cookstove in Gazi Bay.

Conclusion

The three-stone fire is the most commonly used cooking method in Gazi Bay even though there are significant negative social, environmental and health impacts associated with its use. There is strong interest and willingness to invest financially in improved cookstoves, which shows good potential for a successful introduction of a suitable improved cookstove mode. Baselines of average per capita wood usage and indoor air pollution levels have been established and will be used for future efficiency evaluation of the improved cookstove introduction.

Supplementary Data

Supplementary data are available at *BIOHOR* online.

Funding

This work was funded by a grant from the British Council Newton Fund (grant no. 275670159).

Acknowledgements

We would like to give special thanks to Professor John Currie for his invaluable advice and help regarding indoor air pollution. We would also like to thank Dr James Kairo, Agnes Mukami, Sarah Wollring and all other KMFRI staff and students, who helped to carry out this project, and the residents of Gazi and Makongeni villages who gave their time and views.

Author biography

Julia obtained her BSc(Hons) degree in marine and freshwater biology from Edinburgh Napier University and is currently doing an Erasmus Mundus Master's programme in management of marine biological resources. Afterwards, she is hoping to pursue a PhD to evaluate and identify good practice for community based marine management in the global south. She is especially keen on approaches that also contain aspects of sustainable community development, education and poverty alleviation for the local community in addition to marine conservation. She is interested in interdisciplinary research that combines natural and social science research methods and investigates the connection between local communities, sustainable marine management and human well-being.

Statement on co-authors

Mark Huxham was the project supervisor and provided comments and feedback on the manuscript.

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