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Seasonal fuel consumption, stoves, and end-uses in rural households of the far-western development region of Nepal

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Abstract

Understanding how fuels and stoves are used to meet a diversity of household needs is an important step in addressing the factors leading to continued reliance on polluting devices, and thereby improving household energy programs. In Nepal and many other countries dependent on solid fuel, efforts to mitigate the impacts of residential solid fuel use have emphasized cooking while focusing less on other solid fuel dependent end-uses. We employed a four-season fuel assessment in a cohort of 110 households residing in two elevation regions of the Far-Western Development Region (Province 7) of Nepal. Household interviews and direct fuel weights were used to assess seasonality in fuel consumption and its association with stoves that met cooking and non-cooking needs. Per-capita fuel consumption in winter was twice that of other measured seasons, on average. This winter increase was attributed to greater prevalence of use and fuel consumption by supplemental stoves, not the main cooking stove. End-use profiles showed that fuel was used in supplemental stoves to meet the majority of non-meal needs in the home, notably water heating and preparation of animal food. This emphasis on fuels, stoves, and the satisfaction of energy needs—rather than just stoves or fuels—leads to a better understanding of the factors leading to device and fuel choice within households.

1. Introduction

An estimated 2.8 billion people globally rely on solid fuels as a primary cooking fuel. While the proportion of households reliant on solid fuels has decreased since 1980, the actual number of people using those fuels has remained relatively constant due to population growth [1]. The residential sector is one of the largest energy-related sources of carbonaceous aerosol, greater than industrial, transportation, and power sectors [2]. Exposure to household air pollution emissions resulted in an estimated 2.8 million premature deaths in 2015, making it the second largest risk factor for ill health in the environmental and occupational category, after outdoor air pollution [3].

In Nepal, two-thirds of households rely on biomass as a main cooking fuel, and over two-thirds of these users live in rural areas [4]. Consistent with global trends, the actual number of homes using biomass has remained relatively stable at 4 million over the last decade, despite a reduction in the fraction of the biomass-using population [4, 5]. Given Nepal’s reliance on petroleum imports [6] and its large, dispersed rural population (83% in 2011), the continued dependence on biomass to meet residential energy service needs is likely for the foreseeable future. Recognition of the important role biomass plays in Nepal’s current and future energy landscape has prompted government policies and programs for managing forest resources and promotion of more efficient stove
technologies to manage energy demand and mitigate associated health and environmental impacts [7].

Surveys that measure household energy characteristics often record only a primary fuel used for cooking, and occasionally for space heating and illumination (lighting). The existence, importance and impact of other energy needs and uses of fuel remain poorly understood and documented. Identification of only a primary fuel may also miss key household behaviors. Wood may be an important energy source even when it is not the primary cooking fuel, supplying energy for specialized cooking tasks, space heating, bathing, cultural activities, and animal care, for example [8, 9]. These ‘other’ uses can account for a large proportion of household energy budgets [10–14]. The use of solid fuel for space heating has been identified as an important component in the air quality-related health burden in parts of Asia [15]. It might be assumed that homes with access to electricity use it for lighting, but in India, roughly half of the environmental and economic impacts from kerosene lighting occur in electrified homes; the use presumably occurs as backup for supply interruptions or additional lighting services [16]. Identifying only the primary lighting source would neglect this use.

Limited understanding of the distribution of fuels across end-uses and services may result in the misattribution of impacts. In Nepal and many other solid-fuel dependent countries, efforts to mitigate the impacts of residential solid fuel use have emphasized cooking devices rather than other end-uses that may also depend on solid fuels. Interventions based on cooking alone may not fully meet the needs of the home, and will be less effective as a result.

The inability of a single fuel or technology to meet all the service needs of a home leads to use of multiple fuels and technologies, including retaining the old technology, a practice termed fuel or device stacking [17, 18]. Stacking reduces the benefits of programs that intervene by altering fuels or stoves, because the use of traditional fuels and stoves continues [19]. Identifying situations when an intervention meets only a fraction of household needs can give stakeholders more realistic expectations of the likely impact of their investments. Greater understanding of how fuels and stoves meet the diversity of household energy needs can address the drivers of stacking practices and inform strategies to maximize program benefits [8, 9, 20–21].

Characterization of household needs also contributes to understanding the technical and human dimensions that affect adoption and sustained use of interventions [20, 22]. This information can then be used to make more informed program design recommendations, such as a set of intervention devices that deliver specific services [9].

Tabulations of the amounts of fuel used or pollution emitted to the atmosphere (inventories) can also benefit from characterization of baseline residential energy end-uses and practices. Emission inventories describe current energy use and establish a baseline to estimate future transitions. They are inputs to models of atmospheric chemistry and composition [23]. Multinational efforts to increase access to clean household energy have been motivated, in part, by estimates of the impacts of residential-sector emissions on human health and climate based on results from these models [24–26]. Only a few individual end-uses are typically differentiated in most inventories. Thus, most projections of health and climate benefits of fuel or stove transitions have assumed that traditional fuels and stoves are simply replaced entirely with cleaner alternatives [26, 27]. These illustrative studies have identified the magnitude of potential benefits, but without considering the diversity of energy needs, simulated energy transitions may demonstrate unrealistic program impacts. Winijkul et al found that 25%–50% of energy, depending on the region, was not accounted for after using bottom-up estimates to account for cooking, heating and lighting [14]. Their results provide an estimate of the potential importance of these ‘other’ end-uses and energy needs.

Energy needs may also change seasonally [11, 28–30]. Consideration of the temporal dependence of energy consumption that affects specific end-uses may be especially important in regions with cold seasons. Strong positive correlations between residential energy use and heating degree days in Europe, USA, and China demonstrate that seasonal space heating can affect energy use [31, 32]. Fewer studies exist on the seasonality of energy use and fuel demand in most of the Global South. Studies on seasonal household energy use in South Asia find that winter fuel requirements increase relative to non-winter seasons by as little as 10% to a factor of two [33–39]. However, these studies focused on how residential energy demands affect local biomass diversity and supply, rather than on home energy needs. Field evaluations of more efficient cooking devices sometimes capture information on the relationship between fuel consumption and end-uses [12, 40], but are typically performed over short time windows to avoid the influence of seasonal factors.

In this work, we examine how fuels are used to provide energy services across seasons, and the relationship between use of fuel with stoves in the home. We administered fuel assessments in four seasons to a cohort of households in two elevation regions of the Far-Western Development Region of Nepal. In-home measurements of stove-specific fuel consumption were used to assess seasonality in fuel consumption, and questionnaires were used to assess use across different stoves to meet cooking and non-cooking needs.

2. Methods

2.1. Study overview

Seasonal fuel assessments were conducted in households in the High Hills region of the Far-Western
Figure 1. (Top) Study districts of Baitadi (a) and Dadeldhura (b), and the low (blue) and high (gold) VDCs from which participants were sampled from. (Bottom) Average daily temperatures each season with elevation regions colored to match VDC map colors. Error bars correspond to the standard deviation of daily mean temperatures taken over a three-week period each season.

Development Region of Nepal (Province 7). Households were enrolled from villages in four village development committees (VDCs) within the Dadeldhura and Baitadi districts. Two VDCs were in a low elevation subtropical climate zone ('lower elevation,' 1000–2000 m), and two in a high elevation (above 2000 m) temperate climate zone ('high elevation'). Households in the low elevation were closer to protected forest areas ('community forests'), so fuel collection for these homes was more regulated than in the high elevation.

Fuel assessments were conducted over four two-week periods at the midpoint of four seasons: winter (January), spring (April), monsoon (July), and post-monsoon (October). Ambient air temperatures taken outside a subsample of 12–20 kitchens over a three-week period each season were slightly warmer than historic station data but showed similar seasonality. The high region was approximately 2°C colder than the low region, except during the post-monsoon season (figure 1).

A total of 110 households, encompassing 630–700 individuals, were enrolled at the start of the study. Sixty (55%) were in the subtropical low region, and 50 (45%) in the temperate high region. If a household was unable to undergo monitoring during any season due to temporary absence or activities resulting in atypical fuel use, it was excluded from that season but kept in the cohort in later campaigns. No houses requested to be dropped from the study. The dataset contains 786 days of fuel-use data, with 96 households having data for all four seasons with 51 (53%) and 45 (47%) being in the high and low elevations, respectively.

Questionnaires, described in the next section, were translated and administered in Nepali by local surveyors employed and trained by The Centre for Rural Technology-Nepal (Kathmandu, Nepal). All measurement instruments and protocols were approved by the Office for the Protection of Research Subjects at the University of Illinois at Urbana-Champaign.

2.2. Fuel consumption (fuel use) measurements

A Seasonal Kitchen Performance Test (SKPT) was developed to measure seasonal changes in household fuel consumption (fuel use) characteristics. The SKPT is an expansion of the Kitchen Performance Test (KPT), which is a common protocol used to evaluate changes in household fuel consumption resulting from introduction of new cooking devices [41]. The KPT uses fuel weight to quantify consumption, as opposed to participant-reported fuel weights or proxies, and measurements are performed in houses under typical use conditions (uncontrolled).

In the SKPT, and most KPT variants, fuel consumption is quantified by weighing fuels at the beginning and end of a 24 hour period, and repeating this procedure over sequential days. The SKPT expands upon the
KPT in several respects: it apportions fuels to different stoves; it collects more information on the end-uses of fuel and stove use events associated with each stove; and it is structured and worded for repeated use in the same home in order to examine changes over time. Household demographic information and agricultural practices were also collected each season from participant self-reporting.

Fuel consumption was measured over two sequential 24 hour periods in each household and season. Results from a single-season KPT assessment by Berrueta et al showed that most of the variability in population fuel estimates is attributable to between-home differences and that the greatest precision gain occurs from the second day of measurement [42]. It was thus deemed more beneficial in this study to maximize the number of households with a smaller number of repeat measurements in each house.

At the first visit of each season, participants were asked to identify stoves that were used, regardless of frequency. During each visit, the fuel allotted to each stove was weighed with a resolution of 10 g. Fuel allotted to a specific stove was placed beside it, and instructions to use only these fuel piles given to participants. Wood moisture content (%, wet basis) was measured in triplicate at each visit for fuel dedicated to each stove using a Delmhorst moisture meter (J-2000, Delmhorst Instrument Co., New Jersey, USA). Average stove- and day-specific moisture values were used to adjust fuel weights for moisture content. All fuel masses reported are dry mass (e.g. kg dry fuel) even if not explicitly stated. After each 24 hour sample period, participants were asked to recall the stove events of the previous day for each stove, including a description of the task and its approximate duration. The procedure for using reported stove tasks and durations to distribute fuels to end-uses is described in section 2.4. Reported duration of stove use was also used to estimate the average burn rate of stoves used by the family by dividing fuel consumption by the corresponding reported stove use duration (kg fuel hour^−1). The use of fuels other than wood was low in the sample population, so this study focuses primarily on wood, and the term ‘fuel’ in the remainder of this paper implies wood unless otherwise stated.

2.3. Stove categories
We separate stoves into two categories: main cooking stoves and supplemental stoves. The main cooking stove was identified by participants, and was typically where most meals were prepared. Identification of the ‘main’ or ‘primary’ cooking device is common within household energy surveys, despite its subjective interpretation. Supplemental stoves are any other devices where fuel is used for cooking or non-cooking needs. In many household surveys, supplemental stoves are not typically identified, although the fuel used in them would be quantified in a household consumption survey.

We also use several terms to describe seasonal changes in stove use characteristics. Stove ‘prevalence of use’ refers to the proportion of homes using stoves at a given point in time. We intentionally use this term as distinct from the term ‘stove usage,’ which has become synonymous with direct stove use monitoring measurements (SUMs). We use the term ‘activity level’ to describe the rate of fuel consumption for an end-use or stove in a season (e.g. kg wood per day).

Wood stoves were of two types: traditional ‘chula’ (singular ‘chulo’) which were stationary mud stoves (no chimneys) built by members of the home and found in all kitchens, and three-stone fires, which were typically used outdoors but occasionally found inside the kitchen alongside the chulo. Thirty-four households—26 (43%) in the low and 7 (14%) in high elevations—had a rocket-type stationary mud-brick stove with metallic combustion chamber (rocket stoves) distributed as part of Nepal’s National Rural Renewable Energy Program. Too few rocket stoves were present in the sample to have sufficient statistical power for an assessment of these stoves’ performance with a cross-sectional design. The main cooking stove was typically located in an enclosed kitchen separated from the living and sleeping areas of the house. As many as 65% of the houses reported some use of metal heating pans, or ‘makal,’ for space heating. These makals did not burn fuel directly, but carried hot charcoal made in the stoves. Photos of stove designs in the study population are available in the supplementary information (SI) available at stacks.iop.org/ERL/12/125011/mmedia.

2.4. Fuel to end-use apportioning
Daily fuel consumption was distributed across end-uses using participant-reported information on stove tasks and their durations. For each stove, we assumed that the amount of fuel used for an end-use was proportional to the fraction of time spent performing tasks associated with an end-use category. All time corresponding to meal events on a stove were combined into a single ‘all meals’ end-use category. Other end-uses distinguished were drinks, space heating, animal food, and water heating. Any remaining tasks were grouped into an ‘other’ end-use. These fuel end-use estimates were generated for each stove in a house on each measurement day. Other studies have disaggregated hours of stove operation into individual meal tasks (e.g. rice, beans, soup, bread) [9, 21, 40]. We use a similar approach to disaggregate fuel consumption to end-use categories selected to distinguish between cooking and non-cooking needs.

We allocated fuel to end-uses within each home from relative time spent on tasks in order to minimize bias associated with recall-based information in the process of apportioning fuel to end-uses. While the perception of time may vary between people, the relative allocation may be more reliable (e.g. the evening
Table 1. Population characteristics based on participant-report at the time of enrollment, unless presented seasonally. Values in parentheses correspond to one standard deviation.

| Enrolled households | Total | High elevation | Low elevation | Group difference<sup>a</sup> |
|---------------------|-------|----------------|---------------|-------------------------------|
| **Basic household characteristics** |       |                |               |                               |
| Household size       | 6.2 (1.7) | 6.4 (1.6) | 6.0 (1.8) | *                             |
| Age of main cook     | 41 (14)  | 45 (16)  | 38 (12)   |                               |
| Number of rooms      | 5.0 (2.3) | 5.0 (2.3) | 4.9 (2.3) |                               |
| Number of animals    |        |                |               |                               |
| Cows                | 1.4 (0.9) | 1.3 (1.0) | 1.6 (0.8) | *                             |
| Oxen                | 1.2 (0.8) | 1.2 (0.8) | 1.1 (0.9) | *                             |
| Buffalo             | 0.9 (0.9) | 1.4 (1.0) | 0.4 (0.6) | *                             |
| Goats               | 2.9 (3.7) | 3.8 (5.0) | 2.1 (1.7) | *                             |
| Chickens            | 0.9 (2.1) | 1.3 (0.3) | 0.5 (2.2) | *                             |
| Total animals cooked food<sup>b</sup> | 3.5 (1.4) | 4.0 (1.5) | 3.1 (1.1) | *                             |
| **Fuel characteristics (% houses)** |       |                |               |                               |
| Any wood use         | 100   | 100            | 100          |                               |
| Any LPG use          | 6     | 0              | 12           |                               |
| Any kerosene use     | 0     | 0              | 0            |                               |
| Electricity connection | 94 | 91            | 98           |                               |
| Crops that generate ag. residues | | | | |
| Winter               | 62    | 48             | 73           |                               |
| Spring               | 55    | 48             | 57           |                               |
| Monsoon              | 55    | 34             | 73           |                               |
| Post-monsoon         | 92    | 94             | 90           |                               |
| Primary cooking fuel |       |                |               |                               |
| Wood                 | 97    | 96             | 98           |                               |
| LPG                  | 3     | 2              | 1            |                               |
| Primary lighting source |     |                |               |                               |
| Electricity          | 96    | 98             | 93           |                               |
| Other                | 4     | 2              | 7            |                               |
| Wood moisture content (%) |       |                |               |                               |
| Winter               | 13.4 (3.3) | 13.0 (3.4) | 13.8 (3.1) |                               |
| Spring               | 9.1 (2.7)  | 8.6 (1.8) | 9.3 (3.3)  |                               |
| Monsoon              | 24.5 (7.2) | 23.4 (7.3) | 25.4 (7.1) | *                             |
| Post-monsoon         | 15.5 (4.0) | 18.1 (3.3) | 13.9 (3.2) | *                             |

<sup>a</sup> Significant difference between elevation groups at alpha = 0.05 (Student’s t-test or two sample test of proportions).

<sup>b</sup> Total of cows, oxen, and buffalo.

meal took twice as long as drink preparation). The amount of fuel (Fuel) used for end-use, i.e., on stove, j, in house, k, is calculated from the reported duration of total stove use (t) on a measurement day as:

\[
\text{Fuel}_{i,j,k} = \text{Fuel}_{j,k} \times f_{i,j,k} = \text{Fuel}_{j,k} \times \frac{t_{i,j,k}}{\sum_{i=1}^{n} t_{i,j,k}}.
\]

This time-based allocation approach inherently assumes that stove burn rates, or rate of fuel consumption when the stove is operating, are the same for all end-uses in a home on a given day.

3. Results

3.1. Household characteristics

Table 1 summarizes characteristics of the 110 households. Household size averaged 6.2 ± 1.7 (arithmetic mean ± one standard deviation), varying 10% across seasons but never differing significantly between elevation groups (elevation). Homes in the high elevation group had a head of household that was on average 7 years older, and had 0.9 more animals requiring cooked food.

All households reported use of wood and over 97% reported wood as a primary fuel each season. Wood moisture content varied seasonally from an average low of 9.1% ± 2.7% in spring to 24.5% ± 7.2% in monsoon. No families reported use of dung, charcoal (excluding charcoal generated from stove use), or kerosene for any end-use in any season. LPG stoves were present in 10% of houses, but were used sparingly based on the duration between cylinder (14.2 kg) purchases, approximately one year on average. Use of supplemental stoves typically constituted one stove in addition to the main cooking stove. Less than 5% of homes used three supplemental stoves, and none reported more than three. Ninety-four percent of houses had connections to grid electricity, and almost all of those (96%) reported it as their main source of lighting. Houses without electricity connections reported wood or chargeable lanterns as main lighting sources. Grid-powered lighting was supplemented with charged lanterns (e.g. wind-up, charged from grid electricity) or candles during load shedding events (brown-outs).

3.2. Seasonal fuel consumption

Average household and per-capita consumption ranged seasonally from 3.1–9.1 kg day<sup>−1</sup> and 1.0–1.7 kg capita-day<sup>−1</sup> (figure 2). Households using
supplemental stoves consumed 30%–50% more fuel per capita than those using a single stove (p-values < 0.05), except in the monsoon months when the prevalence of supplemental stove use was lowest (table S2). Fuel use peaked in winter, increasing by 3.6 kg day$^{-1}$ (95% confidence interval: 2.9, 4.2) or 0.6 kg capita-day$^{-1}$ (0.4, 0.7) relative to the average of all other seasons, corresponding to a 53% (44%, 58%) increase in per-capita fuel use. Pairwise comparisons among non-winter seasons showed a monsoon to post-monsoon decline of 15% (p-value = 0.023), but no other seasonal differences exceeded 5%. Changes in per-capita fuel use from winter, compared with the average across other seasons, will be referred to as ‘winter changes.’ The average winter change for a household using a supplemental stove in winter was an increase of 66% (52%, 79%), while the change for a household using a single stove was 30% (11%, 48%), a difference of 36% (p-value = 0.0013).

Winter changes could not be attributed to the main cooking stove. Average fuel use in the main cooking stove in winter and monsoon was not significantly different at 1.10 ± 0.8 and 1.07 ± 0.7 kg capita-day$^{-1}$, respectively. Post-monsoon and spring fuel use were also not significantly different at 0.89 ± 0.5 and 0.86 ± 0.6 kg capita-day$^{-1}$. The largest difference in main cooking stove activity levels in any two seasons was 0.2 kg capita-day$^{-1}$, or a 27% increase.

The seasonal change in fuel use was, instead, attributable mainly to fuel usage in supplemental stoves. The prevalence of use of supplemental stoves changed by a factor of four across seasons, reaching a low of 17% in monsoon, and a high of 68% high in winter. Average fuel consumption (activity levels) in supplemental stoves changed by a factor of two across seasons, reaching a low of 0.4 ± 0.4 kg capita-day$^{-1}$ in monsoon, and a high of 0.9 ± 0.5 kg capita-day$^{-1}$ in winter. The monsoon season differed the most from winter in both prevalence of use and activity levels of supplemental stoves. In the full cohort, the supplemental stove accounted for 19% of annual household fuel consumption, and 6% (monsoon) to 32% (winter) of fuel use in any season. Among only homes that used supplemental stoves, those uses accounted for 32% ± 27% (monsoon) to 47% ± 14% (winter) of household fuel consumption.

Although household fuel use was influenced by both the main cooking and supplemental stoves, neither device category was solely responsible for seasonal trends in household fuel use. Supplemental stoves drove most of the observed winter change, but the seasonal pattern in household fuel use was affected by changes in both stove categories. In monsoon, activity levels on main cooking stoves was high relative to other non-winter seasons (figure 2, middle). This fuel increase was offset, however, by a low prevalence and activity level of supplemental stoves (figure 2, right). The total household fuel use in monsoon was then similar to other non-winter seasons (figure 2, left). In winter, when household fuel use was highest, activity on main cooking stoves was also elevated, but also accompanied by high supplemental stove prevalence and activity.

Figure 3 is a visualization of the annual fuel consumption for the average home in each elevation, distributed among seasons, stove categories, and end-uses. The flow diagram reflects the temporal dimension of fuel use, and the relationship between fuel, stoves and energy needs. The finding that household fuel use is highest in winter and similar among other seasons is shown by the relative sizes (widths) of the seasonal nodes. The relative sizes of the stove nodes demonstrate the division of fuel use between main and supplemental stoves. Colors identify different seasons, showing that houses at high elevations use more fuel relative to those at lower elevations at most times of the year.

Figure 3 also encapsulates the following findings: (1) by end-uses, meals account for the largest single share of annual fuel use, and total non-meal end-uses account for approximately one third of annual fuel requirements. (2) Water heating and preparation of animal food account for over half of the

Figure 2. Average per-capita fuel consumption per day (kg capita-day$^{-1}$) by season and stove. (Left) Fuel consumed in all stoves of the house, (middle) only the main cooking stove, and (right) only the supplemental stoves. Marker sizes are proportional to the prevalence of use of the stove each season. A main cooking stove was used every season, so the markers for the main cooking stove and household (total) panels are scaled to 1.0. Error bars correspond to the 95% confidence interval of the mean.
3.3. Stoves and fuel end-uses

Figure 4 (left) presents the proportion of reported stove events by season, stove, and end-use. A difference in the distribution of end-use events provided by each stove type is apparent in every season. The main cooking stove was dominated by meal and drink preparation, while the supplemental stoves were used for tasks involving the heating of large pots, either for animal food or heating water. During non-winter seasons, main cooking stove events dominate household event profiles.

Total hours of stove operation increased in winter, as did hours spent on most end-uses (figure 4, right). Additional time was spent on meal preparation (+1.3 hours), supporting the hypothesis that meal-making stoves might be used to provide warmth. Formal space heating also increased in winter, but even at its peak accounted for less than 5% of total events and hours of stove use. Two of the largest increases in stove operation—animal food (+0.7 hours), and water heating (+1.3 hours)—were predominantly performed on supplemental stoves. These additional stoves significantly altered the household stove event profiles, although they did not alter uses of the main cooking stove.

3.4. Elevation and seasonal fuel consumption

Per-capita fuel use among homes at high elevations was greater than those at low elevations by at least 30% (p-values < 0.03) in all seasons but the monsoon. Fuel end-use distributions in the average high elevation home showed a larger fraction of fuel going to water heating and animal food in non-winter seasons; the latter is consistent with the greater number of animals requiring cooked food (figure 5, right).

The increase in per-capita fuel use in winter relative to other times of the year was greater among homes at higher elevations. Compared to the average per-capita consumption during spring, monsoon, and post-monsoon, the average home used 77% (59%, 94%) more fuel in winter in the high elevation and 35% (22%, 49%) more in the low elevation (figure 5, left), a difference of 42% (p-value = 0.0001). Fuel used on the main cooking stove in winter increased modestly at high elevations (15%) but remained unchanged in the low-elevation homes, further demonstrating the important role of supplemental stoves in driving seasonal household fuel use trends. End-use profiles in winter were very similar between elevation groups, suggesting that no individual end-use was responsible for the large difference in relative winter change between elevations.
Figure 4. (Left) Seasonal proportion of reported stove events by end-use and stove. (Right) Average hours per day spent performing end-use activities (colors) by season (symbol).

Figure 5. (Left) Boxplots of pairwise changes in daily per-capita fuel use between winter and the average of non-winter seasons (monsoon, post-monsoon, spring) by elevation. Values greater than 0% indicate an increase in winter fuel use. Changes in supplemental stoves are not shown due to the seasonality of their use, but can be inferred from household and cooking stove trends. (Right) Average division of fuel consumption among end-uses by elevation and season.
3.5. Reported stove use and fuel consumption comparisons

Participant-reported stove use characteristics and fuel consumption are often assumed to be unreliable in many research and evaluation contexts. For this reason, physical measurements are often recommended, such as stove surface temperature that indicates usage or weighed fuel to indicate consumption. Seasonal trends of self-reported stove use collected in this study, however, closely reflected those of measured fuel weights (figure S5), suggesting that survey-based measures may be useful for estimating seasonality in fuel consumption. Spearman correlation coefficients of stove use duration from questionnaires and direct measures of fuel consumption were moderate: winter ($\rho = 0.75$), spring ($\rho = 0.52$), monsoon ($\rho = 0.41$), and post-monsoon ($\rho = 0.62$). An estimate of the average winter fuel consumption based on reported stove use durations (relative to winter) and a single non-winter season direct fuel measurement campaign would have been within 20% of actual fuel use. Visual comparisons between reported stove use and measured fuel consumption are presented in the supplementary information.

Estimated burn rates of stoves varied little across season, implying that seasonal changes in fuel use were driven predominantly by shifts in the duration of stove operation. The annual average fuel burn rate across all homes was $1.1 \pm 0.5$ kg hour$^{-1}$. Season-specific burn rates were within 20% of each other, ranging from 1.0 (winter) to 1.2 kg hour$^{-1}$ (post-monsoon). With the exception of the post-monsoon ($1.2 \pm 0.6$) and winter ($1.0 \pm 0.4$), no statistically significant seasonal differences in burn rates were measured ($p$-values $> 0.05$).

4. Discussion

Fuel assessments were performed in a panel of 110 Nepali households over four seasons to quantify seasonal differences in fuel consumption, and its association with stoves and end-uses. On average, winter consumption was twice that of other measured seasons. This winter increase was attributed primarily to greater prevalence of use and fuel consumption by supplemental stoves, not the main cooking stove. End-use profiles showed that supplemental stoves were used for the majority of non-meal tasks, such as heating water and cooking animal food, and that their activity levels peaked in winter. Differences in the relative increase of fuel use in winter across elevation regions were not clearly associated with end-uses. The results of this study emphasize the importance of considering energy needs and their role in determining residential fuel requirements and reliance on multiple stoves (stacking). This emphasis on fuels, stoves, and the satisfaction of energy needs—rather than just stoves or fuels—leads to a better understanding of the factors leading to device and fuel choice within households.

Even limited use of traditional devices (more than 10%–20% of total cooking time) can lead to unsafe levels of exposure [19]. The supplemental stoves used by families in this study accommodated larger pots than their main cooking stoves, and the end-uses were consistently different. Thus, alternatives to traditional chula that address only cooking needs would not be expected to fully displace supplemental stoves. Cooking stoves are the focus of most household energy interventions, but addressing non-cooking needs is also necessary to achieve displacement of all polluting devices. Supplemental stoves in the study population accounted for 20% of annual fuel consumption on average, and 0%–63% for individual homes. In homes at lower elevations, where the traditional chula had been replaced with a rocket stove as the main cooking stove, 45% of fuel was still used in supplemental stoves in winter, so that half of the fuel in the household ‘escaped’ an intervention.

It would be reasonable to assume that space heating was the main activity associated with observed winter fuel increases, but only a small fraction of fuel use was attributed to space heating in any season. Space heating needs were typically met by moving charcoal made in stoves through rooms of the house in metal pans. In other seasons, this leftover charcoal would be discarded, following practices common in much of South Asia. Field questionnaires indicated that some users lit the cooking stove 15–30 min earlier in winter to warm the kitchen. Both of these space heating practices may have contributed to the modest (14%) increase of fuel use measured on the main cooking stoves in winter. This winter change was similar to the 10% winter increase reported in homes in the Tibetan Plateau, where heating pans are also used [29]. In households monitored in this study, an intervention designed to address only space heating would likely have only minor impact on altering use of existing stoves and fuel consumption. Instead, an improvement of winter combustion might be better achieved by providing large stoves suitable for animal food preparation and water heating, although this may do little to alter space-heating practices.

A greater winter fuel change in homes at higher elevations was not clearly associated with differences in energy needs and may instead reflect differences in fuel availability. Elevational differences in the winter fuel change reported in South Asia are few and inconsistent, ranging from a modest positive association between winter change and elevation [36] to a negative association [33, 35]. None of these previous studies examined energy needs. In the present study, the proportion of fuel attributed to each end-use was similar across regions, so that end-uses caused seasonal differences but not elevational differences. It is possible that differences across elevation groups here may have arisen from fuel access. Homes at low elevations were closer to protected forest areas and faced more fuel collection restrictions.
Such restrictions may have led to fuel use practices that promoted conservation of fuel. A longitudinal analysis of Nepal’s Living Standards Surveys reported that establishment of protected forest areas within 20 km of a village was associated with a 30%–70% decrease in household biomass consumption [43], while having no measurable effect on use of purchased fuels.

Neither physical measurements of fuel use nor questionnaires alone would have captured the relationship between seasonal fuel use, stoves, and energy needs reported by this study. Fuel assessments alone would have yielded seasonal consumption patterns and winter change estimates, however, an understanding of the factors driving these patterns and changes was possible because direct physical measures of fuel use were complemented by insights on fuel end-uses from questionnaires. Although direct measures of physical energy use parameters are typically preferred, questionnaires may still provide reasonable approximations in some contexts. In this study, an estimate of average fuel consumption in winter based on reported changes in stove use and a single non-winter direct fuel measurement campaign would have been within 20% of actual fuel use. Previous studies that have compared physical measures of stove usage and surveys have generally shown that basic stove use parameters, such as whether a stove was ever used [21, 44], tend to have closer agreement than parameters requiring finer scale recall, such as the duration of cooking events or number of events in a day [45–47]. The reliability of questionnaires to quantify physical energy use characteristics, however, will vary across populations and study contexts, so piloting designs remains important. Continued efforts to leverage the benefits of both measurement approaches will be needed to understand the mechanisms affecting household energy transitions, and develop impactful solutions.

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