Evaluation of usage and fuel savings of solar ovens in Nicaragua

by
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ABSTRACT:

I evaluated solar oven usage and wood consumption in northern Nicaragua during both the rainy and dry seasons using surveys, temperature dataloggers placed in solar ovens, and direct measurements of wood consumption. Solar oven owners surveyed reported usage on 79% of days during the dry season, and 41% of days during the rainy season. I compared these results with oven temperature records, and found elevated oven temperatures (>50°C) on 70% of days with reported use during the dry season, and 47% of days with reported use during the rainy season. However, wood consumption measurements showed no statistically significant difference between days with solar oven usage and days without, suggesting that frequency of usage is not linearly related to fuel savings. In this report, I discuss possible explanations for this discrepancy, and implications for future research and solar oven implementation.

INTRODUCTION:

1. Solar cooking background

Over one third of the world's population still uses solid biomass (wood, dung, and crop residues) for cooking, lighting, and/or heating, causing serious problems with respiratory health and deforestation (Ruiz-Mercado et al., 2011). Indoor air pollution from biomass combustion has been shown to increase the risk of acute respiratory illness among young children by two to three fold, (Fullerton et al., 2008) and has been linked to 1.9 million premature deaths worldwide (Wang et al., 2013). In Central America, indoor air pollution has been associated with 37,000 premature deaths every year, and is ranked one of the top five causes of death and illness in Guatemala, Honduras and Nicaragua (Wang et al., 2013). Meanwhile, the developing world also loses 15 million hectares of forest every year (Nandwani, 1996), at least in part due to fuelwood consumption for residential cooking. Gather firewood also requires immense time and energy, and helps perpetuate socioeconomic inequality in the developing world. In Central America, men typically gather fuelwood, consuming on average 10 hours per week, while women take charge of the cooking, spending on average 4 hours per day in the kitchen breathing in toxic fumes (Wang et al., 2013). Most traditional wood stoves do not have chimneys, so smoke is released directly into the cooking area.

a) **b)**

Figure 1. a) A woman in San Diego, a village outside of Condega, cooks on a traditional wood stove without a chimney. **b)** A man carries a load of fuelwood back to Condega, in many cases a task carried out daily.

Requiring no fuel and producing no emissions, solar cookers hold the potential to greatly reduce biomass fuel consumption in sunny parts of the developing world, improving public health and economic conditions while simultaneously preserving the environment. Solar cookers have garnered attention in development circles for decades, but two obstacles have blocked widespread dissemination: funding and cultural acceptance. Though cheap by first world standards, in most cases solar cookers remain prohibitively expensive for the people who need them most, and maximal solar cooker usage also often requires a significant change in lifestyle or diet.

Initially, solar cooking was often thought of as an engineering problem with an engineering solution, and as a result, solar cookers across the globe have collected dust because their owners have found the benefits of solar cooking not worth the inconvenience. In more recent years, solar cooking promoters have put much more effort into increasing acceptance (e.g. Tucker, 1999; GTZ and DME, 2002), but cooking with sunlight is not always easy, and many challenges remain.

2. Fuel savings calculations

Fortunately, in recent years a possibility has arisen to merge the two main obstacles blocking solar cooker dissemination, by converting proven usage into funding through the carbon credit market. By reducing the combustion of solid biomass, solar cookers hold the potential to mitigate a small amount of greenhouse gases. If one can quantify this mitigation potential rigorously but simply, one can now fund solar cookers on a much larger scale than previously feasible by obtaining carbon credits. Several solar oven projects have already been funded in this way through the UN Clean Development Mechanism (CDM), including the Indonesian Aceh 1 project in 2005 (Seifert, 2005), involving hundreds of parabolic cookers, and more recently several large scale distribution projects in China (CDM, 2010).

However, despite growing solar cooker dissemination, relatively few studies have been conducted to rigorously quantify the reductions in wood consumption, and the calculations involved in obtaining carbon credits still involve many assumptions that detract from their credibility. The first large solar cooking project involving intense monitoring came in the late 1990's, when the German Agency for Technological Cooperation (GTZ) sponsored a solar cooking field test in South Africa with the South African Department for Minerals and Energy (DME). Though the project failed in its main objective to establish a market for solar cookers, monitoring of solar cooker usage and fuel consumption revealed usage for 38% of meals, resulting in a 38% reduction in fuel consumption (Biermann et al., 1999). Later studies revised this figure downwards to between 25% and 31% (Wentzel & Pouris, 2007). Likewise, in 1999, a study of solar ovens in a refugee camp in Kenya found usage on 42% of days, resulting in fuel savings of 25% (Lankford and Knudson, 1999). This study also found a large difference in fuel savings between average solar oven users, and those who had been trained more extensively and agreed to use their solar ovens as much as possible. This result suggests that acceptance and usage of solar cookers may be more important than any technical specification in determining fuel savings.

Both of these studies determined fuel savings by daily measurements of fuel loads, a time consuming method that is sometimes hard to generalize to larger populations. As such, recent efforts have focused on creating models to approximate fuel savings, using indirect data that is easier to obtain. The researchers involved in the South African solar cooker field test have since promoted the "meal-portion" method for determining greenhouse gas mitigation, by which each meal cooked for one person in the solar oven is assumed to save about 400g of carbon emissions, a number determined by controlled cooking tests (Grupp & Wentzel, 2002). They also developed a remote use meter that measures oven temperature and solar irradiance to determine the number of meal portions successfully cooked in a solar oven, using the standard equation for energy produced by a flat plate solar collector (Grupp et al., 2009). Projects that have received funding through the CDM have calculated greenhouse gas savings via the amount of time for which solar cookers are used, multiplied by an independently-determined constant involving the efficiency of the traditional stoves used, the energy content of fuel saved, and the power produced by the solar cooker (Seifert, 2005). This approximation assumes that solar ovens produce a constant amount of power whenever they are used, and that each unit of energy produced by a solar oven results in an equal savings in fuel energy.

Unfortunately, these assumptions often do not hold true in practice, and it is unclear whether these models for wood savings represent the actual quantity saved. In this report, I present results from studies of solar oven usage and wood consumption in Estelí province, Nicaragua, and discuss the relationship between them. Despite relatively high levels of solar oven usage, I found only negligible reductions in wood consumption, suggesting that the link between solar cooking and wood savings is not as simple or direct as previously thought (at least in the Nicaraguan cooking context). As I will discuss below, there are many possible explanations for this result, ranging from problems with subjective surveys, to the types of food cooked in solar ovens, to the natural variability of wood consumption from day to day. Regardless, this result suggests that future research on fuel savings should go beyond controlled experiments to include more extensive *in situ* measurements of wood consumption. Furthermore, it suggests that in the future, solar cooking projects should pay attention not only to how often solar cookers are used, but also to what they are used for, and whether or not this usage actually replaces consumption of traditional fuel sources.

3. Project outline

I began fieldwork for this project during the summer of 2013, when I lived in Condega, Nicaragua, for 10 weeks, working with the Association of Women of the Rising Sun of Condega (AMSONAC). I conducted interviews and surveys in 3 nearby villages, (El Jobo, San Diego, and Potrerillo) where a total of 32 women had received solar ovens between 2008 and 2010. While I was in Nicaragua, AMSONAC also conducted oven construction workshops in the villages of El Horno and Casa Blanca in the neighboring municipality of Pueblo Nuevo, and I was able to attend part of one of these workshops in order to observe and help with the construction, and conduct some interviews and surveys with new oven owners. I also placed temperature dataloggers in some solar ovens to provide an objective measure of usage, and conducted measurements of wood consumption, greenhouse gas emissions production, and solar oven thermodynamic performance.

Located in a subtropical region at a latitude of 13ºN, Condega experiences a rainy season from May until November, and it quickly became clear that in order to obtain a definitive measurement of solar oven usage and wood savings, I would need to return during the dry season (December through May), when I was informed that usage would be much higher. Thankfully, last fall I received a research grant from CASEP to continue my research, and in January 2014, I returned to Nicaragua for 7 more weeks of fieldwork. During this time I continued most of the same measurements from the previous summer, and also briefly visited two other solar oven organizations in Nicaragua—the Cooperative of Solar Women of Totogalpa (COOMUSOT), in Sabana Grande, and Foundation for the Promotion of Solar Energy to Nicaraguan Women (FUPROSOMUNIC), in Granada—to compare their projects with those of AMSONAC. I also greatly expanded measurements of daily wood consumption, including a week in the village of Santa Rosa both before and after solar ovens were constructed there in March. This report will focus on the results from the more recent field work conducted during the dry season, with references to rainy season data for comparison. I also performed various tests of solar oven thermodynamic performance, but due to the large number of uncontrolled variables, no useful conclusions could be drawn, and I will have to reserve these results pending further research.

EXPERIMENTAL METHODS:

In 2013, I conducted interviews with a total of 57 women in Condega, asking questions related to wood acquisition and consumption, solar oven usage, and household demographics. In 2014, I interviewed 44 women to explore issues related to perceived advantages and disadvantages of the solar oven, as well as reasons for not cooking specific foods. I conducted cooking surveys with 45 women in 2013 and 55 in 2014, on which the women recorded the quantity of each food item they cooked each day in both their wood stove and solar oven, as well as the duration of cooking or reason for disuse. I collected surveys at two-week intervals, at which time I distributed incentives of $0.80 for each week filled out correctly (the equivalent of the wage for of two hours of manual labor in Condega).

I also placed Thermochron iButton temperature dataloggers in the ovens of 26 families in 2014, for a total of 553 days of temperature records; in 2013, I collected temperature records from 16 different families on a total of 447 days. In each case, the dataloggers were placed in the front right corner of the ovens, such that they were shaded by the oven door, in order to provide a more accurate reading of oven air temperature. In 2013, data from iButtons was downloaded at two-week intervals using a Windows laptop with OneWire Viewer software. In 2014, a laptop was not available, so dataloggers were collected at three-week intervals, and data was downloaded onto a computer in the AMSONAC office. Dataloggers were typically returned to ovens the following day.

In order to measure daily wood consumption, I visited households each day to weigh wood to be used for the next day, as well as any wood that remained from the day before. In 2013, I conducted this test for 5 days in the villages of El Jobo and San Diego, comparing the wood consumption of 9 families with solar ovens to that of 10 families without. In 2014, I repeated this 5-day study with 5 solar oven owners in San Diego, to provide a comparison between the rainy and dry seasons. I also monitored the wood consumption of 9 solar oven owners in Potrerillo for 7 days in February and 7 more days in March, to compare consumption on days with solar oven usage to days without. Finally, I monitored the wood consumption of 10 families in Santa Rosa for a week both before and after they received solar ovens in March, to directly measure the impact of solar oven acquisition. In 2014, wood moisture content was also measured using a Testo 0560 Pocket PRO Moisture Meter.

I also conducted controlled cooking tests to measure the quantity of wood required to cook the individual food items that make up the bulk of Nicaraguan cuisine: tortillas, corn, beans, rice, and boiling water for coffee. Between 2013 and 2014, I conducted at least 10 trials for each cooking task, varying food quantity. In each case, I removed all wood, ash, and coals from the stove before cooking, and weighed the quantity of wood both before and after cooking, as well as any coals and ash produced. I measured the time elapsed from the moment of ignition to the moment when the cook declared the food ready.

Finally, throughout both periods of field work, I monitored solar irradiance with a Kipp and Zonen SP Lite2 pyranometer, placed on the roof of the AMSONAC office and connected to a Meteon datalogger. I also monitored ambient temperature with a 1921G Thermochron iButton, placed in the shade behind the AMSONAC office.

RESULTS & DISCUSSION:

1. Solar oven usage

Overall, solar oven usage reported on surveys was quite high: on average, solar oven owners reported use on 79% of days during the dry season, and 42% of days during the rainy season (see Figure 2). It is not surprising that there is such a stark difference in usage between the rainy and dry seasons, but, as shown in Figure 3, the difference does not appear to be mainly due to differing levels of sunlight. Average solar irradiance between 9am and 3pm during the dry season was found to be 570±206 W/m^2, as compared to 467±154 W/m^2 during the rainy season. Yet, even on days with similar average solar irradiance, usage during the rainy season was much lower than during the dry season. We can explain this by considering that during the rainy season, solar oven owners often fear that even if the sun is shining in the morning, storm clouds could gather at any moment, not only preventing food from cooking but also potentially damaging the solar oven. Meanwhile, though usage and solar irradiance show some correlation, the trend leaves much of the variation unexplained, suggesting that sunlight is not the most important factor in determining solar oven usage.

Solar oven usage also differed dramatically between villages, and this trend most likely reflects a decrease in usage over time of ownership (see Figure 4). Families in Santa Rosa, Casa Blanca, and El Horno all have had ovens for less than one year, while families in Potrerillo, San Diego, and El Jobo have owned their ovens for 3, 4, and 5 years, respectively. In fact, survey results drastically understate this trend, because they do not include solar oven owners whose ovens were broken during the survey period, or owners who had returned their ovens to AMSONAC due to lack of use. When I left in Nicaragua in March, in El Jobo 4 out of the original ten ovens were too broken to be used, as well as 2 out of ten in San Diego, and 1 out of 12 in Potrerillo. In most cases, the ovens considered broken would require only minor maintenance to fix, such as broken door locks or a rotting reflector, but the AMSONAC employee charged with repairing ovens made little noticeable progress throughout my time in Nicaragua.

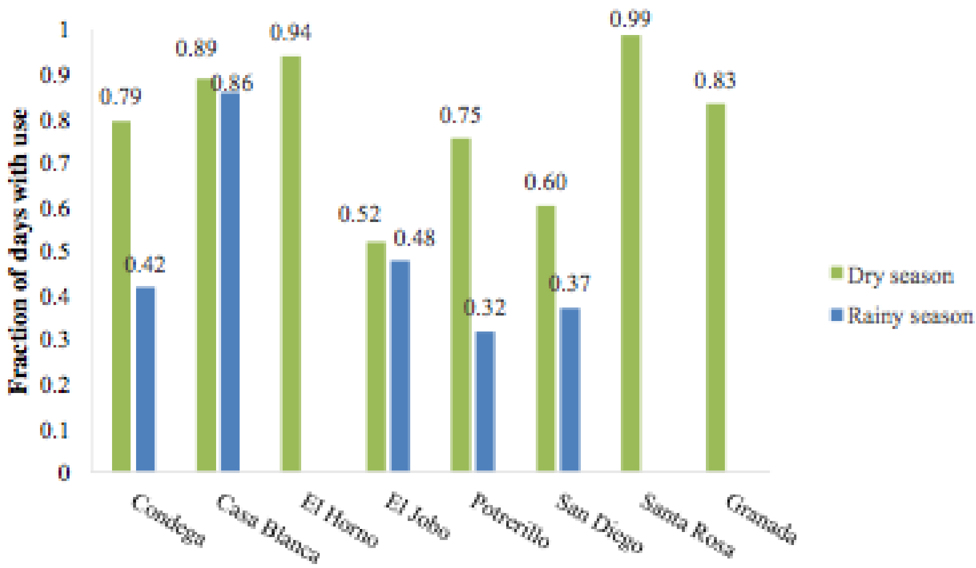

Figure 2. Level of solar oven usage in each village, expressed as a fraction of total days surveyed, in both the dry season (January-March 2014) and the rainy season (June-August 2013). In El Horno, Santa Rosa, and Granada, solar cooking surveys were only conducted during the dry season.

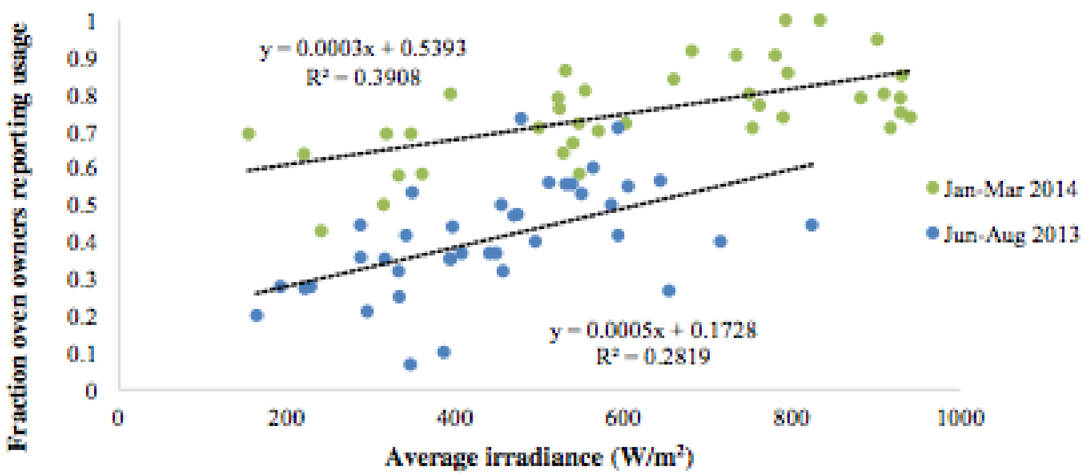

Figure 3. A comparison of solar oven usage with average solar irradiance between 9am and 3pm each day both during the rainy season and dry season shows little correlation between amount of sunlight and usage. However, regardless of irradiance, usage is much lower during the rainy season, suggesting that the fear of rain damage plays a large role in determing usage.

In addition, two of the original solar oven owners in both San Diego and El Jobo had returned their ovens due to disuse. One had an injury that prevented her from rotating the oven during the day, one found she had nowhere to put the oven after adding an extension to her house, and two told me that, for most of the year, there was not enough sun for them to cook most food items. Finally, 1 woman in each of San Diego, El Jobo, and Potrerillo had started working since acquiring a solar oven, and as a result used their solar oven much less frequently. I did not include these women in surveys because they were not available for survey distribution and collection.

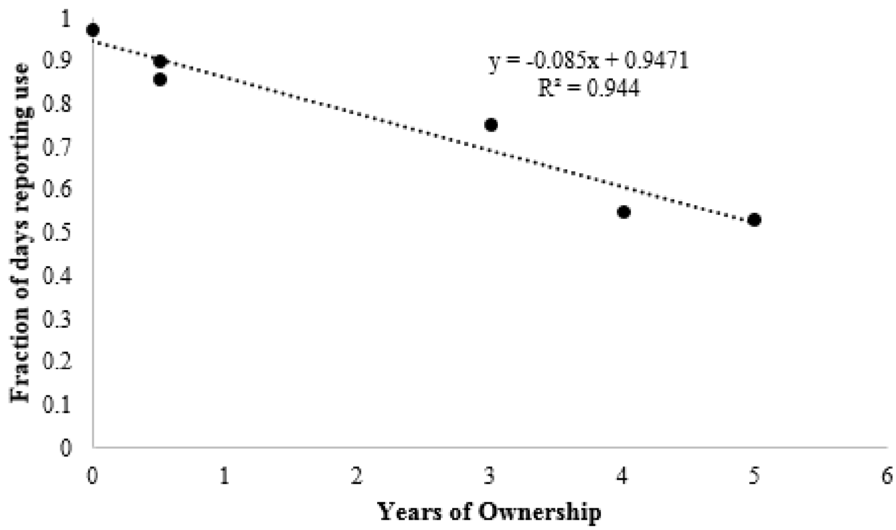

Figure 4. Solar oven usage tends to decrease over time, even when considering only functional ovens.

2. Wood consumption

Unfortunately, the results of wood consumption tests showed no statistically significant fuel savings from solar ovens in Condega. Four separate wood consumption tests corroborate this result: the comparison of wood consumption by 9 oven-owning families and 10 wood stove-only families in El Jobo and San Diego during the rainy season, the comparison of wood consumption by 5 oven-owning families in San Diego during the rainy and dry seasons, the comparison of wood consumption by 9 families in Potrerillo on days with solar oven usage and days without, and the comparison of wood consumption by 10 families in Santa Rosa before and after receiving solar ovens in March 2014 (see Figure 5). Although there was a small reduction in wood consumption in each case, the error far outweighs this difference. I found the wood savings overall to be 10±69%, and a t-test found no significant difference between wood consumption on days with use and days without. While a few families experienced significant savings, others actually consumed more wood on days when they used their solar ovens than on days when they did not. I analyzed these results with unpaired t-tests, and found that, at the 95% confidence level, only two families experienced significant savings on days with solar oven use (60% and 39% savings, with p-values equal to 0.0002 and 0.0006, respectively), while one family used significantly more wood (79%, with a p-value equal to 0.012). All three families were in Santa Rosa.

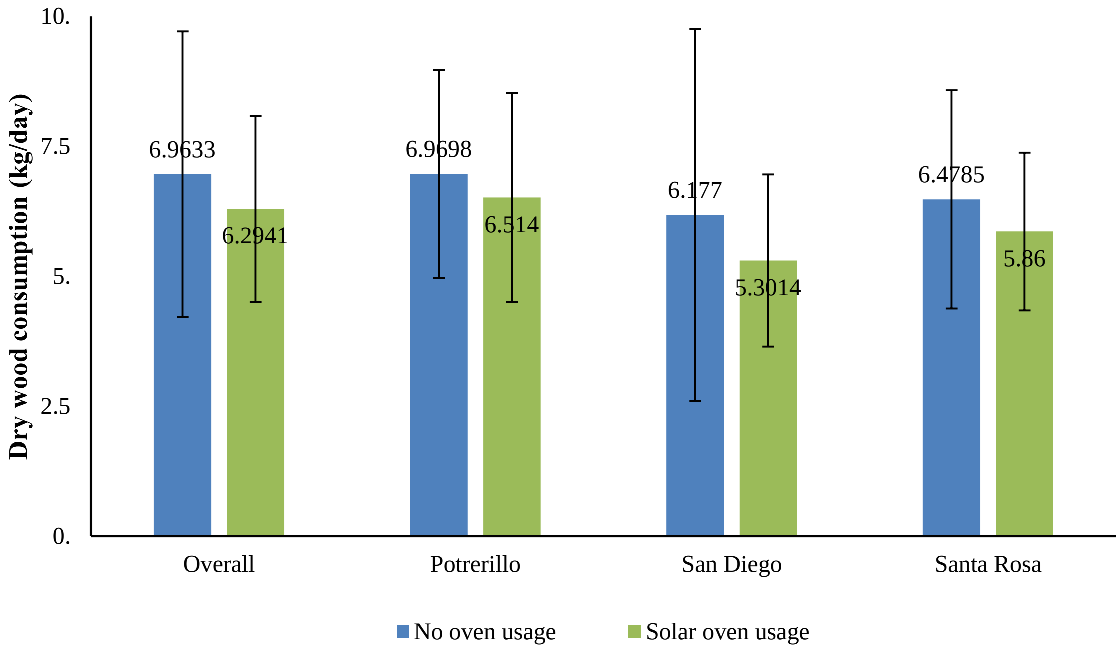

Figure 5. Measurements of wood consumption in Potrerillo, San Diego, and Santa Rosa show slight reductions on days with solar oven use, but error far outweighs perceived reductions. I conducted all measurements daily for 14 days in Potrerillo and Santa Rosa, and 10 days in San Diego. I adjusted all wood weights by the experimentally-measured moisture content to obtain dry masses.

This surprising result begs the question, why don't families save wood when they use their solar ovens? In general, the main feature of the wood consumption data is great variability, both between different families and between days. What lies behind these differences? A definitive answer will require much more research, but my data does provide some clues.

3. Factors affecting wood consumption

First, it is possible that solar oven owners cooked a greater total amount of food on days when they used their solar ovens. In three families in Santa Rosa, the husband was working in Honduras when I measured wood consumption before the oven construction workshop, but had returned when I repeated measurements after ovens had been completed. Indeed, these families all consumed slightly more wood after the workshop, though they were not the only ones to do so, and disregarding them does not drastically change the overall result.

Another possibility is that surveys do not reflect actual usage. In other words, it is possible that solar oven owners are not actually cooking food in the solar oven when they claim to do so. Comparison with temperature records reveals that surveys significantly overrepresent solar oven usage. Solar oven owners who had temperature dataloggers in their ovens reported usage on 71% of days during the dry season and 34% of days during the rainy season, but oven temperature exceeded 50°C on only 70% and 47% of these days, respectively. This result means that solar oven usage can only be confirmed on a total of 50% of days during the dry season, and 16% of days during the rainy season, figures far lower than those determined by results from surveys alone.

There are several possible explanations for this discrepancy. First, given that 12% of days showed temperature elevation but no reported usage, it is possible that some of the mismatch is due to faulty memory: some reported use on days without temperature elevation may have actually occurred on days with temperature elevation but no reported use. However, we know that this does not account for all of the discrepancy, because on at least some days, women admitted that the oven heated up but they did not place anything inside. On other days, women admitted they tried to cook in the solar oven, and recorded this on the survey, but then had to finish the food in the wood stove when the oven failed to heat up. In addition, it is possible that women sometimes over reported their usage in an attempt to please the researchers and solar oven donors.

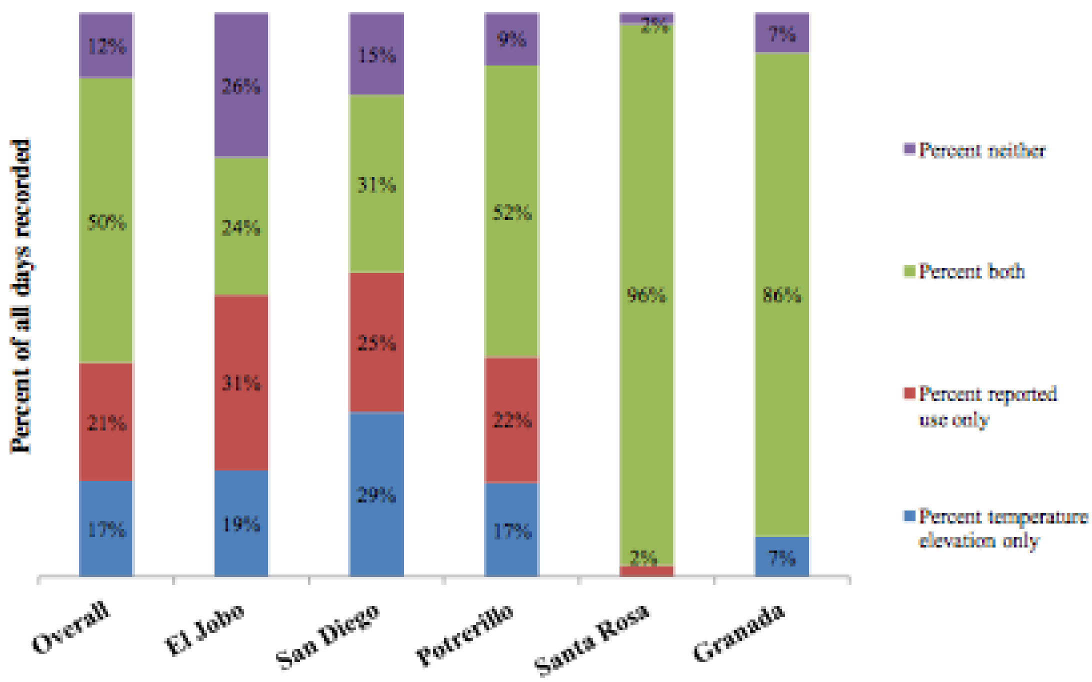

Figure 6. Comparison of survey results with temperature records during the dry season shows significant discrepancies; usage can only be confirmed by both surveys and temperature dataloggers on 50% of days. Green represents days where usage was reported and oven temperature exceeded 50°C, blue represents days where only the latter occurred, red represents days where only the former occurred, and purple represents days where neither occurred.

In either of these latter two cases, it is possible that during the wood consumption tests, there were some days when solar oven usage was reported, but food items were not successfully cooked in the solar oven. Unfortunately, not all subjects of the wood consumption tests had dataloggers in their solar ovens, so it is hard to make a definitive conclusion either way. Nonetheless, for those who did have dataloggers in their ovens during the wood consumption studies, most reported solar oven usage coincided with elevated oven temperature. I compared wood consumption again, counting only days with both reported usage and temperature elevation as days with solar oven usage, but this did not make any significant difference in the result.

A third possible explanation for the lack of wood savings is that the kinds of foods cooked in the solar oven did not replace a significant amount of wood consumption. This hypothesis is corroborated by survey results, which show that for the most part, the food items cooked most often in the wood stove are rarely cooked in the solar oven, regardless of the season. In fact, when comparing results from wood surveys on days with solar oven usage and days without, I found no significant difference in the number of food items cooked on the wood stove. As discussed above, surveys are notoriously unreliable, but this result still suggests that, at least in some cases, food cooked in the solar oven acts as a complement to food cooked in the wood stove, not a replacement.

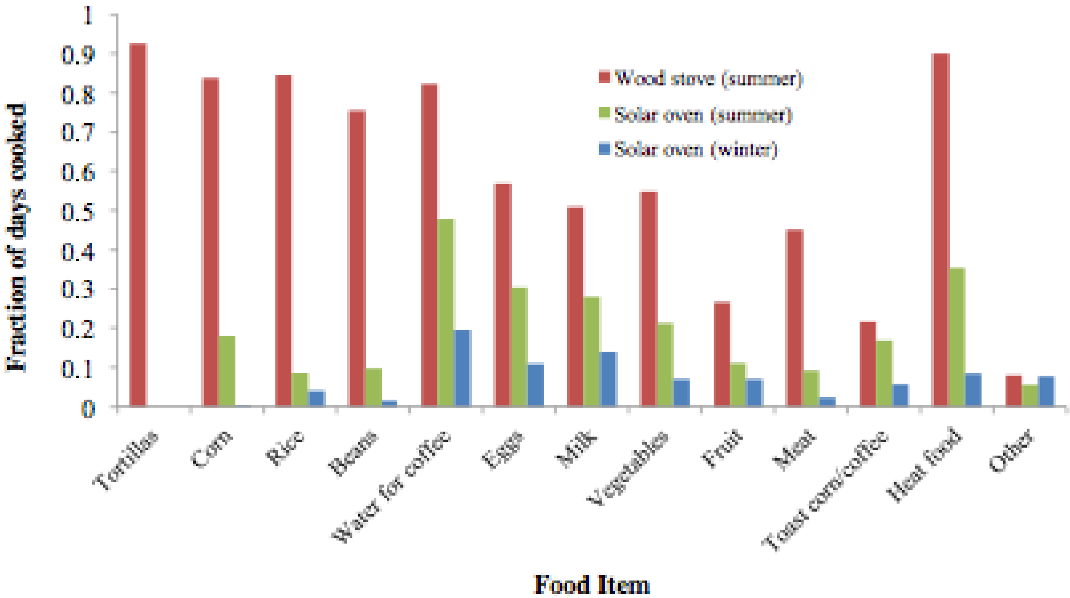

Figure 7. Comparison of cooking practices in both the wood stove and solar oven by food item shows strong differences. Each result is expressed as the fraction of all days on which each food item was cooked. In Nicaragua, winter is synonymous with the rainy season, while summer is synonymous with the dry season.

As shown in Figure 7, the cooking tasks that make up the bulk of Nicaraguan cuisine are preparing tortillas, corn, beans, rice, and heating water for coffee. Of these five tasks, solar ovens in Condega are only regularly used to heat water for coffee. I measured the wood consumption of each of these five food items, and found that tortillas, beans, and corn require by far the most wood to cook (see Figure 8). I then used data from surveys regarding the frequency and quantity of each cooking task to approximate the percentage of total daily wood consumption taken up by each food item. I found that tortillas and beans each likely make up over 20% of daily wood consumption (see Figure 9). Combined, I found that tortillas, beans, and corn make up about two thirds of daily wood consumption. Unfortunately, tortillas cannot be prepared in a solar oven, but it seems clear that in order to capture all possible wood savings, women must cook beans and corn in their solar ovens. Thus, the question arises, why don’t women cook wood-intensive food items in their solar ovens more often?

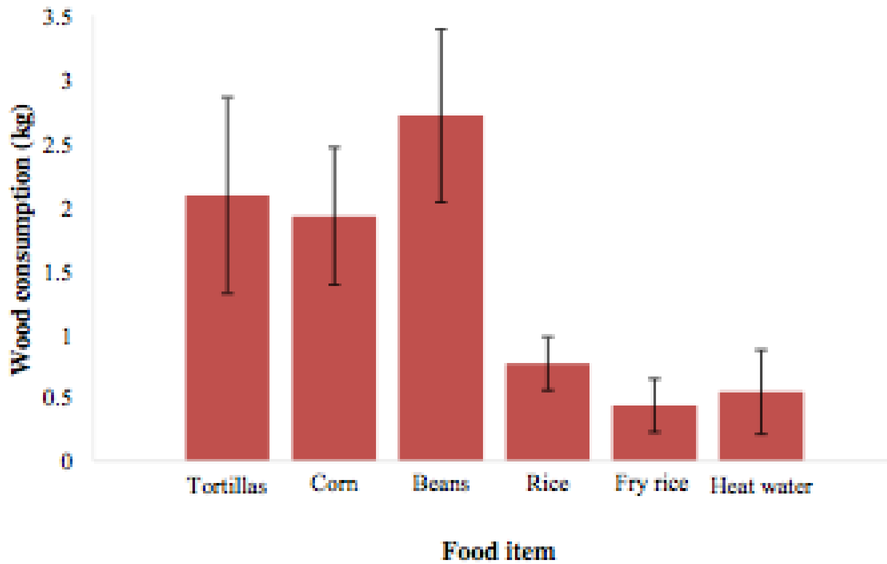

Figure 8. Comparison of wood consumption by food item for the five food items most commonly prepared on wood stoves in Nicaragua, as determined by controlled cooking tests. I did not adjust results for moisture content, because many tests were performed in 2013, when a moisture content meter was not available.

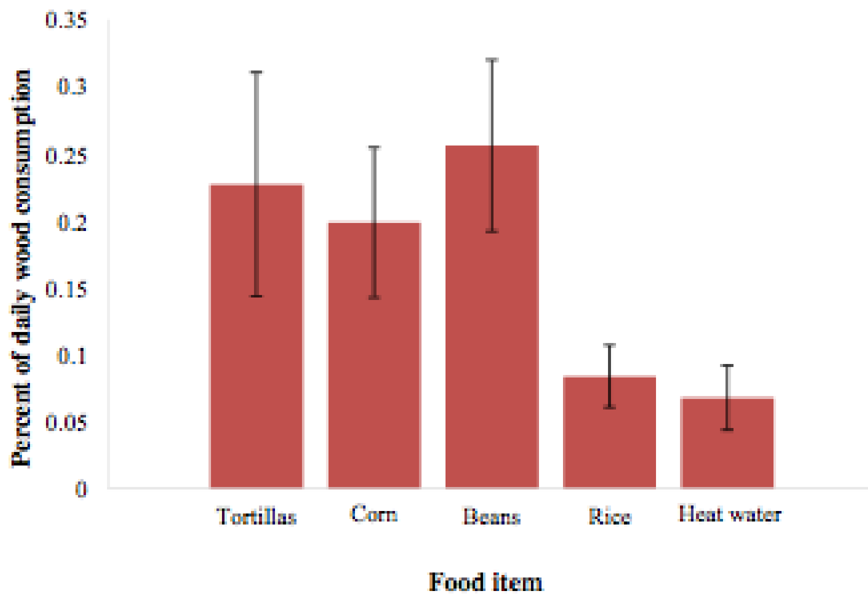

Figure 9. Wood consumption by food item, expressed as a percent of total daily wood consumption. Results from controlled cooking tests were adjusted for the average quantity and frequency with which each food is cooked, then divided by the overall average wood consumption determined by daily measurements.

Based on results from interviews, we can see that most women fall into two camps: when it comes to food they do not cook in the solar oven very often, they either do not think there is enough sunlight for the food to cook in a timely fashion, or they have never tried to, or both (see Figure 10).

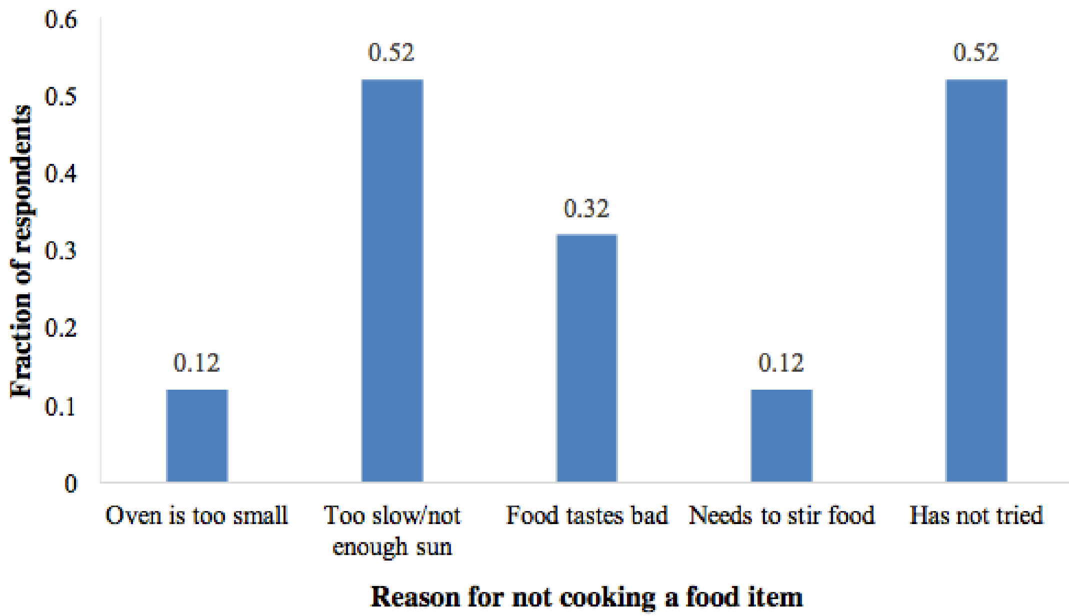

Figure 10. Reasons for not cooking a particular food item, expressed as a fraction of interviewees giving each response. Total is greater than one because some interviewees gave multiple answers.

Indeed, part of the problem may be the weather: situated in the Segovia Mountains, Condega receives more cloudy weather than most of western Nicaragua. Even though it only rained 5 out of the 50 days I was in Nicaragua during the dry season, I observed significant cloud cover (clouds covering more than 40% of the sky) on at least part of 35 days, and on all of 10 days. Many people told me that this weather pattern is typical for the region: only March and April are consistently sunny, while the rest of the dry season, stretching from mid-November through mid-May, is often cloudy. In fact, when comparing the transmittance (the ratio of solar irradiance hitting the ground to solar irradiance entering the upper atmosphere) during the dry season with that during the rainy season, one finds surprisingly little difference until late February. This lack of sunny weather may help explain the decrease in usage rate over time of ownership: if a woman tries to cook a food item in her solar oven and fails, she is less likely to try again. As mentioned above, two of the four women in Condega who voluntarily returned their solar ovens to AMSONAC cited lack of sunny weather as the reason.

I also spent one week conducting field work in Granada, during which time it was completely sunny on all but one day. I was told that unlike Condega, Granada receives consistently sunny weather most days throughout the dry season, from November through May. Interestingly, over 80% of those interviewed in Granada claimed to cook beans in their solar oven somewhat frequently, as opposed to 17% in Condega, and 73% claimed to cook meat somewhat frequently, as opposed to 27% in Condega. On surveys, solar oven owners in Granada reported cooking beans, rice, and meat over 30% of days, as opposed to less than 10% in Condega. Of course, 6 days is a very small sample size, and cooking practices in Granada are very different from those in Condega; for example, people in Granada typically buy their tortillas, and so cook neither tortillas nor corn. Obviously, more research must be conducted in

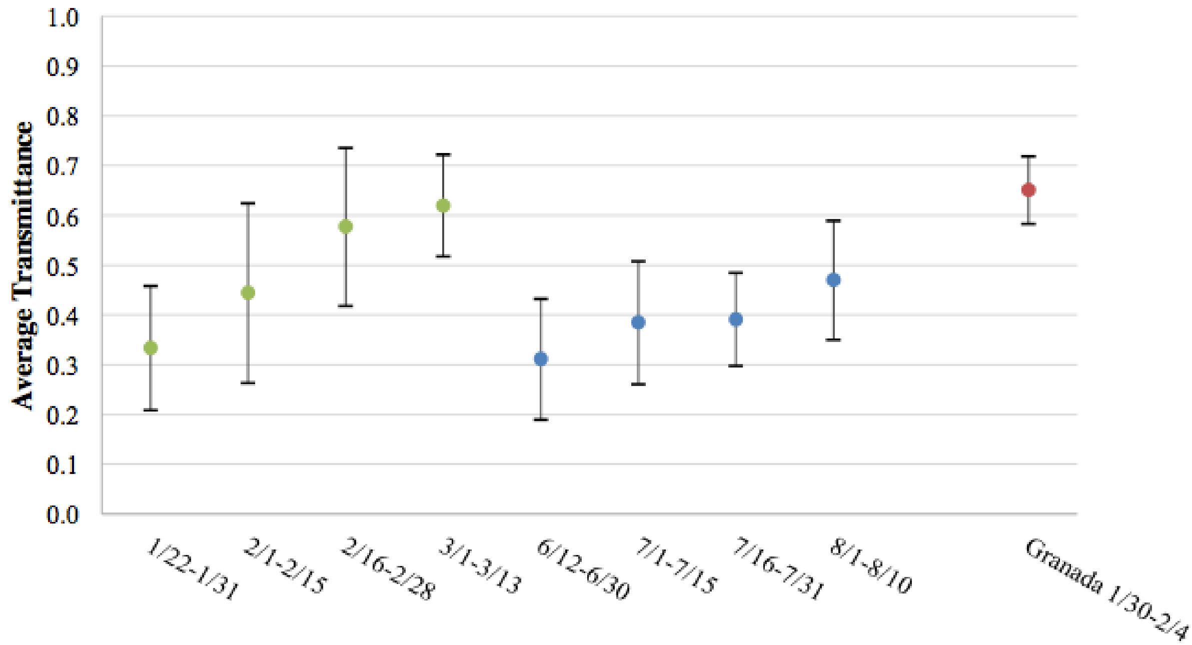

Figure 11. Average solar transmittance during each two-week period of field work in Condega reveals that major differences between transmittance in the rainy (blue) and dry (green) seasons only begins in late February, leaving a small window for solar cooking before the rainy season begins again in mid-May. Values of 0.7 and higher are generally considered to represent completely sunny weather (Personal communication: Karl Lapo, Ph.D. candidate in atmospheric sciences at University of Washington). The high values of solar transmittance in Granada (far right, red) are consistent with perceptions that Granada is sunnier than Condega, though the small sample size of transmittance measurements (6 days) limits generalizability.

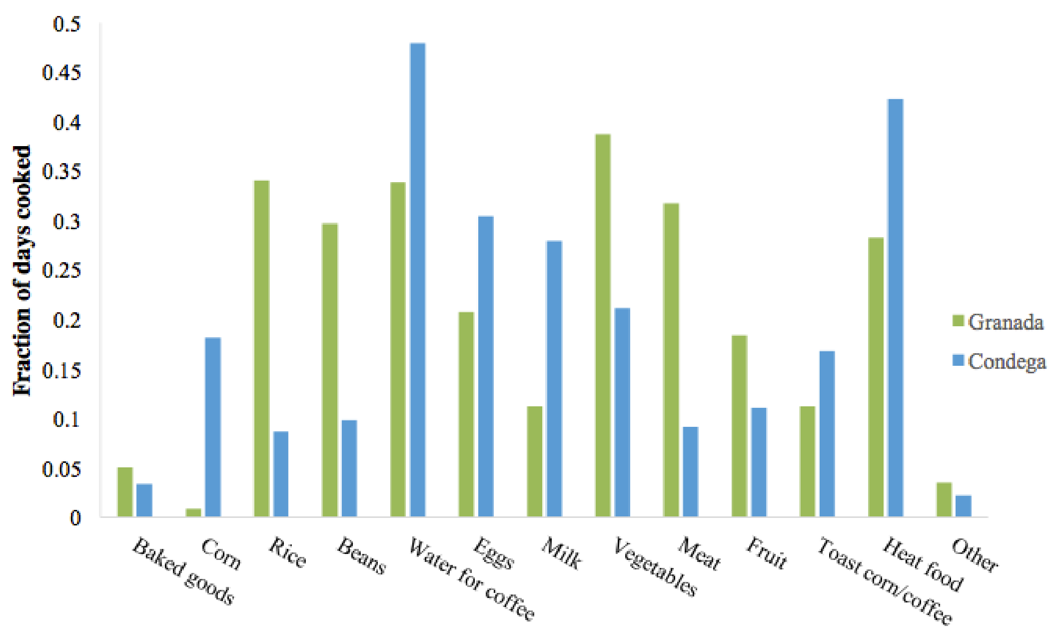

Figure 12. Comparison of survey results from Condega with those from Granada indicates that families in Granada use their solar ovens for wood-intensive food items like beans and meat much more frequently than solar oven owners in Condega.

Granada before a definitive conclusion can be reached. Nonetheless, these results are consistent with the hypothesis that Condega's cloudy weather contributes to less solar cooking of wood-intensive food items, such as beans and meat.

The other reason women commonly gave for not cooking a particular food item was simply that they had never tried. Often, women explained further that they did not think it possible to cook said food item, suggesting that lack of usage for some food items is due to lack of awareness. Indeed, after I encouraged women to try cooking beans and corn in their oven in March, several began to do so on their own accord, and thanked me for convincing them to experiment. This suggests that the solar oven project in Condega could benefit from more demonstration and follow-up to make sure that not only are women using their solar ovens, but using them to their full potential.

However, another possible explanation for the lack of experimentation is lack of perceived need. Despite deforestation, northern Nicaragua still has relatively abundant firewood, such that collecting firewood does not represent an extreme burden as it does in other parts of the developing world. Moreover, in essentially all households, men collect the firewood, so women do not have as much direct incentive to reduce their wood consumption as they might otherwise. When asked why they feel it is important to reduce wood consumption, 40% of interviewees pointed to saving work for their husbands, while 53% mentioned protecting the environment, 13% mentioned resource scarcity, and no one mentioned respiratory health. In other words, while essentially all solar oven owners would like to consume less wood, they likely do not feel an urgent need to do so. Interestingly, the family that I found to have saved by far the most wood (59%) after acquiring a solar oven was also the only one in which the women collected the firewood, walking 5 hours twice a week to do so.

In general, it appears that solar ovens are not in high demand in Condega. Before deciding to hold a solar oven construction workshop in Santa Rosa, AMSONAC offered the opportunity to three other villages, but could not garner enough interest in any of them to warrant following through with the workshop. Likewise, AMSONAC had left a solar oven in Santa Rosa for demonstration purposes almost a year prior to the workshop, but aside from the woman who kept the oven at her home, not a single family had tried cooking with it.

Considerations of perceived need for saving fuelwood could also explain why women in Granada use their solar ovens to cook beans so much more frequently. In urban areas, women must buy their cooking fuel (typically a combination of wood, gas, and/or charcoal), and so solar oven usage of food items that significantly reduce fuel consumption delivers immediate economic benefits. This observation is consistent with the results of the South African Solar Cooker Field Test, which found highest usage of solar ovens in urban areas with grid electricity, where families must pay relatively more for their cooking fuel (Wentzel & Pouris, 2007).

However, my results also indicate that cooking wood-intensive food items in the solar oven does not necessarily lead to increased wood savings. Considering only the days on which families cooked corn or beans in their solar ovens, I found no significant difference with other days with reported solar oven usage. One possible explanation for this is that most wood stoves in Nicaragua have two burners, and often two food items are cooked simultaneously, such that if one were cooked in the solar oven but the other still on the wood stove, wood consumption might remain about the same. In addition, essentially all women in Condega begin the day by frying tortillas, a wood-intensive cooking task that creates a lot of coals. Thus, controlled cooking tests may overestimate the wood consumption of beans and corn, which, in some cases, may be cooked largely with heat from the coals produced by cooking tortillas. Unfortunately, without further research, I can do no more than speculate.

CONCLUSIONS:

Based on my results, I must conclude that solar oven usage in Condega does not necessarily lead to wood savings. A few families with high levels of usage did experience significant wood savings, but the high variability of wood consumption between days and between families outweighed these isolated cases. This result suggests that solar oven projects should not only be judged by levels of solar oven usage, but also by measured differences in wood consumption as well. The disconnect I observed between high levels of solar oven usage on the one hand, and negligible wood savings on the other, suggests that wood consumption is not well modeled by controlled tests. My data contradict the "meal-portion" model advanced by Grupp and coworkers, as well as the time-to-savings calculations used by CDM-funded projects, suggesting the need for more extensive study of wood consumption in Nicaragua *in situ*. One way to explore these issues would be to spend an entire day shadowing each cook in a village, weighing all food placed on the wood stove and all wood consumed. This experiment would be time consuming and challenging, but may be the only good way to directly measure the relationship between wood consumption and cooking tasks performed.

In addition, my results suggest that solar oven users in Granada may experience more fuel savings, possibly due to sunnier weather and higher fuel costs that encourage conservation measures. Unfortunately, I did not have time to conduct thorough measurements of fuel savings in Granada, which will be necessary to reach a definitive conclusion. Families in urban areas like Granada typically use a mix of a variety of fuels, including electricity, charcoal, wood, and natural gas, meaning that a method will need to be developed to compare different fuels on one scale in order to calculate overall savings.

A third avenue for future research is increased usage of temperature dataloggers as oven usage monitors. To my knowledge, prior to this study temperature dataloggers had never been employed to monitor the long-term usage of solar ovens, despite their extensive usage with improved biomass stoves (Ruiz-Mercado et al., 2012), and the development of a prototype device for measuring both temperature and solar irradiance inside a solar oven by researchers involved with the South African solar cooker field test (Grupp et al., 2009). Temperature dataloggers have proved extremely useful to my work, but I feel that with more research, they could be used to monitor solar oven energy production and wood savings as well as basic usage. During my time in Nicaragua I conducted numerous cooking tests in an attempt to establish a relationship between solar irradiance, oven temperature, and cooking power, but variable weather conditions prevented me from obtaining definitive results. Future research should focus more on measuring food temperature instead of oven temperature, possibly by leaving thermometers in waterproof capsules, and asking solar oven owners to place them in any food item when it is placed in the solar oven. Alternatively, one might use a datalogger such as the Thermochron DS1923 to simultaneously measure temperature and relative humidity, assuming that relative humidity increases when water-containing food items are heated in the solar oven.

However, possibly the most definitive conclusion from this project is that in Condega, solar ovens are used frequently, and reach cooking temperatures on many of these days. Despite variable weather conditions, women generally seemed very excited about their solar ovens, and the technology clearly has received a high degree of acceptance in the communities. Results from a parallel project carried out by Sarah Vukelich in February and March suggest that women find the solar oven construction workshops extremely empowering, and that the experience often has ripples in other parts of their lives by raising self esteem and building a sense of community. The reason why this acceptance apparently does not lead to wood savings remains somewhat of a mystery. For decades, solar oven projects have faced the challenge of gaining acceptance for a new and somewhat unusual technology. In Nicaragua, it appears that this challenge has been overcome. My results suggest that now a new challenge awaits.

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