Tracking the Leakage of Development Goods Using iBeacon Technology

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Abstract

The leakage of development goods is a major challenge for governments and a preoccupation of development practitioners and academic researchers. Although commonly reported and lamented, leakage is challenging to quantify and trace. We address this evidentiary blind spot by piloting the use of iBeacon technology to track how village elders distribute solar lanterns within off-grid communities in western Kenya. We provide evidence on the efficacy of the technology for detecting the lanterns and tracking their movement. We analyze why some households received lanterns and others did not, finding compelling and unexpected patterns. Nearly all lanterns remained within the participating communities, contrary to expert predictions. Although we find some evidence for the salience of social connections between village elders and lantern recipients, most households with a lantern met the priority distribution criterion. We find also evidence of lantern distribution to households with needs along dimensions beyond our designated criterion. Our findings run against the common equation of "leakage" with malfeasance. They also underline the potential for political economy research leveraging iBeacon technology at scale.

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1 Introduction

The leakage of development goods—defined broadly as deviations from program guidelines about who should receive items distributed in the context of aid programs—is a major challenge for governments and the aid industry, and a preoccupation of development practitioners and academic researchers. Every year, millions of dollars of farming inputs, relief food, pharmaceutical supplies, bed nets, and other development goods wind up in the hands of people other than their intended beneficiaries.[1] In some instances, this leakage amounts to outright theft, and may feed criminal networks and reinforce the power of politicians and bureaucrats who are complicit in the diversion of these items. Frequently, however, the leakage is simply a form of misallocation that is assumed to undermine the benefits that the goods were designed to bring. Either way, practitioners view the leakage of development goods as having a particularly negative impact on the poorest and most vulnerable populations, who are the most frequent recipients of humanitarian aid (USAID, 2024). Pervasive leakage also risks undermining support for development aid in donor countries.

Although commonly reported and lamented, the leakage of development goods is challenging to quantify and characterize precisely. In part, this is because deviations from program guidelines, not to mention outright theft, tend to be hidden. But it is also because the sorts of development goods that governments and aid agencies regularly distribute—fertilizer, maize, antimalarial medications, farm tools, and, increasingly, cash—are very difficult to trace once they have been distributed within a community. Common approaches to tracking leakage, such as perception-based surveys (e.g., Transparency International 2024; Olken 2009) or comparisons between goods allocated and received (e.g., Reinikka and Svensson 2004; Golden and Picci 2005; Olken 2006, 2007; Niehaus and Sukhtankar 2013; Banerjee et al. 2018), can provide only rough estimates of what may have gone missing. In addition, these approaches tell us little about where the goods may have gone or when in the distribution process the leakage may have occurred. This evidentiary gap hinders our ability to devise strategies to minimize leakage. It also creates challenges for developing a deeper understanding of why local actors entrusted with distributing development goods may diverge from program criteria, as well as how leaked goods flow through markets and patronage networks once they are diverted. Such questions are critical for both policymakers and students of political economy.

We address this evidentiary blind spot by piloting the use of iBeacon technology to track solar lanterns distributed by village elders in off-grid communities in western Kenya. iBeacon technology relies on Bluetooth tags that can be tracked remotely as they move through space; for example, commercial versions of the technology include Apple AirTags and Tiles, commonly used for locating lost keys and luggage. When

[1] A representative set of reports of such leakage include Bate (2011), *Malawi 24* (2016), Michael (2018), Darden (2019), Corruption Watch (2020), and *Daily Nation* (Zambia) (2021).

affixed to an item and tracked via a systematic monitoring program, these tags make it possible to follow that item from its initial distribution point to its ultimate beneficiary without direct contact with the item's distributor or recipient. iBeacon technology thus offers a significant advantage over other approaches to studying leakage, which either make inferences from aggregate measures of missing goods (thus providing no information about the paths that the goods may have taken or who may have ultimately received them) or observe allocation decisions directly via audits and other forms of overt monitoring (thus alerting actors to the fact that their behavior is being watched—and likely changing that behavior).

Although iBeacon technology offers significant advantages for studying the distribution of development goods, its use raises challenging ethical questions. A first objective of the study is therefore to demonstrate a set of protocols for deploying this technology ethically. We discuss at length below how our project design sought to balance the potential benefits of using iBeacon technology with the protection of and respect for the communities in which we distributed the tagged lanterns.[2]

Our second objective is to assess the efficacy of the technology for detecting and tracking the movement of development goods distributed in a real world setting. We find that the technology works extremely well for this purpose. We were able to detect 98.8% of the lanterns we distributed in our study area, as well as follow their movement across households during the ensuing eight weeks of tracking. Our results suggest that iBeacon technology offers a powerful tool for policymakers and practitioners interested in unobtrusively taking inventories of items (for example, to detect whether or when they leave a business, storage facility, or distribution supply chain) or in learning how goods move through markets and communities. This ability makes the technology particularly well suited for collecting outcome data in studies comparing the relative efficacy of different modes of distribution (for example, via local elites, community committees, or direct democracy)[3] and offers potentially large payoffs for both policy design and theory building. Our research thus offers a proof of concept for an especially promising approach to deepen our understanding of the leakage of development goods, a seemingly ubiquitous and pernicious threat to aid efficiency. Bolstering knowledge in this area is particularly important in our current era of strained aid budgets and heightened scrutiny of development programming (Dreher, 2025).

Our third objective is to use the information gleaned from the tracking to learn where the tagged items went and, through that knowledge, to better understand when and why deviations from program guidelines occurred. Notwithstanding the challenges stemming from the small sample size within our pilot study,

[2] We discuss these issues at greater length in a separate paper focused on the ethics of employing remote sensing technologies in development research. An anonymized version of that paper is available here.

[3] As examined, for instance, in Olken (2010), Beath, Christia and Enikolopov (2017), or Voors et al. (2018)

we were able to identify some consistent and significant patterns. First, virtually all of the solar lanterns remained in and were dispersed within the intended recipient communities. This finding was contrary to our own expectations, which were that at least some of the village elders would sell the lanterns and pocket the money. It was also contrary to the expectations of local development researchers, whose median prediction was that only a slight majority of lanterns would remain within the communities in which they were originally distributed. Second, while village elders distributed most lanterns to households meeting the priority criterion, other household characteristics, such as lived poverty and lacking a connection to the electric grid, were more prevalent among recipient households than non-recipient households, regardless of whether the recipient household met the priority criterion. This pattern suggests that the village elders tasked with distributing the lanterns drew on local knowledge about which households would benefit most and adjusted their distribution strategies accordingly. Third, while we find some evidence that village elders prioritized ineligible recipients with whom they had strong social ties, such connections were less powerful and universally salient than the literature might have led us to expect (e.g., Bates (1974), Chabal and Daloz (1999), Hodler and Raschky (2014), De Luca et al. (2018)). Finally, lanterns moved across households after the initial distribution. While the number of such cases is insufficient to allow us to draw strong conclusions about what may explain these movements, the patterns we observe raise the possibility that original recipients engaged in welfare-enhancing voluntary transfers to households that may not have met the program criteria but were needy on other dimensions.

Taken together, our findings provide a contrast to the widespread depiction of local African elites as predatory actors seeking to capture development resources for their own ends and beholden to social pressure to favor their kin. Our results suggests the need to rethink the equation of "leakage" with malfeasance. We caution, however, that, unlike the lessons from the piloting of the iBeacon technology itself, the findings about who received the lanterns are necessarily context-specific. Whether we would find the same patterns in other settings is an empirical question—albeit one that scholars could easily test using the technology and approach we describe here.

2 iBeacon Technology and its Application

iBeacon technology relies on two components: (1) uniquely identifiable tags or beacons and (2) a reader, which in our case was a smartphone with Bluetooth capability running a customized beacon scanning and logging application. Beacons broadcast signals that advertise their presence, and readers search for nearby beacons, recording the unique name and signal strength of any beacon they detect.[4] Beacon detection thus allows a researcher to infer that a tagged item is somewhere within the reader's detectable range (approximately 20-60 meters for the technology we employ).[5] Inferences about precisely where the tagged item is located can be sharpened by drawing on information about the reader's location, the beacon's signal strength (which provides a proxy for the distance between the beacon and the reader), and the locations of nearby dwellings or other structures where the researcher has reason to believe the item might be located.

We tested the efficacy of the iBeacon technology by placing beacons within 244 solar lanterns and distributing them in roughly a dozen contiguous off-grid villages in western Kenya.[6] We then used the technology to identify the households that received the lanterns, as well as the movement of lanterns across households (and, potentially, out of the study villages) over time.

Solar lanterns are valued goods in the communities in which we worked. About 80% of households in our study villages lack a connection to the electricity grid. Although most households have solar home systems, these systems are inadequate to meet reasonable demands for electric lighting.[7] Even households that are connected to the grid would find solar lanterns valuable, as electric power tends to be used for just a handful of stationary lights, whereas a lantern offers portability. Moreover, during prior focus groups in nearby villages, we repeatedly probed whether an alternative good might be more valuable. Participants never suggested an alternative good, instead affirming the value and desirability of having a solar lantern. Solar lanterns are often sold in local markets, although they are usually second-hand and of unverified quality; thus, a demand exists for this product even if local resources are insufficient to optimally meet this demand.

Prior to distributing the lanterns, we mapped the geolocations of all 2,824 buildings in the study villages. These buildings include roughly 1,600 distinct households (many households contain multiple dwellings or outbuildings—e.g., kitchens, animal shelters). The mapping exercise linked buildings to households, so

[4] Further details on the iBeacon technology are provided in Appendix A.

[5] Commercial iBeacon products like AirTag and Tile leverage a wider network of smartphone users, enabling a beacon's owner to track its approximate location even when the owner herself is not within range of the beacon. In contrast, our application collected data only from project iPhones.

[6] We delivered the lanterns to village elders in mid-2022, who distributed them quickly thereafter. All data collection concluded over one month prior to the general election. For reasons elaborated below, we are deliberately vague about the details of our study site, including the precise number of villages in which we worked.

[7] The median household in our sample has three rooms, a three-bulb solar home system, and a latrine outside the home. Thus, the typical household does not have enough light to illuminate each room, the pathway to an outdoor latrine, and inside the latrine for nighttime use.

that a lantern detected in a building could be associated with a specific household.

We tasked village elders with the distribution of lanterns within participating communities. Chosen by community members in consultation with the local chief, village elders are non-salaried public officials who resolve local disputes; enforce government regulations; and serve as contacts for government representatives, NGOs, and other outsiders seeking to distribute goods and services in their communities (Mutua and Kiruhi, 2021). We worked with village elders precisely because tasks such as solar lantern distribution are routine within their work, a fact which the village elders confirmed in post-study interviews. We provided the village elder in each village with between 12 and 34 lanterns (with the number proportional to village population), along with instructions to distribute the lanterns within their own village, prioritizing households containing children under five years old.[8] We justified this criterion by citing that young children might need help during the night; if these households lack electric lighting, they commonly use kerosene lamps that present a danger to the children's health and safety (Lam et al., 2012). Local focus groups consistently endorsed this distribution criterion.

Over the subsequent eight weeks, field officers carrying iPhones running a customized app conducted five rounds of tracking missions in each village.[9] During each mission, they were instructed to walk within 20 meters of every building—close enough to detect a tagged lantern if one were present.[10] The app recorded the field officers' walking route as well as the presence and signal strength of any beacons detected during their mission. Figure 1 provides an example of the data collected during a trial tracking mission. The yellow line indicates the field officer's walking path. The orange segments indicate the intervals on that path when a beacon was detected, with the pink dots indicating the points of maximum signal strength for each detected beacon.

We matched detected beacons to households by combining data on the geolocations of buildings, the field officer's walking path, and the signal strength of any detected beacons at each point on that path. We began by identifying the point on the walking path that was closest to each building's previously recorded geocoordinates. To account for measurement error in both building locations and beacon signal strength, which can be affected by dense objects located between the beacon and the reader, we identified the segment of the walking path within a one meter radius of this most proximate point. This is the segment where a

[8]On average, we provided approximately one lantern for every seven households.

[9]The study area was selected so that the tracking mission for each village could be completed in a single day.

[10]Our tracking data indicate that field officers came within 20 meters of 91% (and within 30 meters of 95%) of all mapped buildings on average during each tracking mission. Deviations occasionally occurred when fencing restricted access or if household members refused to permit the field officer to approach, a request that we honored. See Appendix B for further details.

Figure 1: A Tracking Mission.

beacon's signal strength should be strongest if a beacon is located within that building.

In instances where we detected a given beacon in close proximity to a single building or to multiple buildings belonging to a single household, we matched the beacon to that household.[11] Such straightforward cases were somewhat rare, however, representing only approximately one quarter of household match instances. Owing both to the moderate density of buildings in some areas of our study villages and to the relatively broad signal range of our beacons, most beacons were detected in proximity to multiple buildings belonging to distinct households (see Appendix E). In such instances, we assigned the beacon to the building (and associated household) for which the signal strength was highest on average in the most proximate segment of the field officer's walking path. Figure 2 provides a stylized illustration. In this example, the same beacon is detected in the segments most proximate to two different buildings: h_2 and h_3, generating two potential matches. However, because the beacon's average signal strength is greater in the segment in closest proximity to h_3, we infer that h_3 is the building in which the lantern is located.

Once we had matched beacons to households, we sought to understand why some households contained beacons (i.e., solar lanterns distributed as part of our project) and others did not. To do this, after the conclusion of the five rounds of tracking missions, we conducted a household survey during which we

[11] For simplicity in this explanation, we refer only to households. However, our mapping exercise and subsequent analyses also included non-household complexes (e.g., schools or churches) to which matches were occasionally made. In practice, the vast majority of matches (91.45%) involved household-associated buildings. Post-tracking interviews with village elders confirmed that lanterns were occasionally kept in non-household buildings—for example, churches serving the sick or elderly.

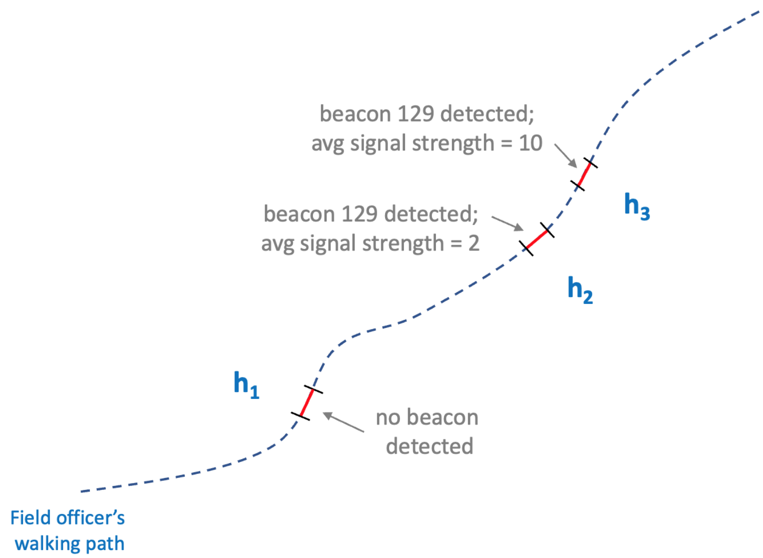


Figure 2: Matching Beacon Sightings to Households.

attempted to interview every household in which a lantern was ever detected plus a roughly equally sized random sample of other households in each village (total $n = 566$).[12] The survey collected information about household characteristics including, crucially, whether the household contained any children under five years of age (the stated priority criterion for distribution), other aspects of household composition, the sources of lighting within the household, other potential indicators of need, and social connections between household members and the village elder. The objective was to learn what made households that had received the lanterns different from households that had not, thus providing insight into the village elders' distribution

[12]We have survey data for 62.5% of households meeting our basic match criteria under our current algorithm. Matched households may lack survey data for several reasons. Survey enumerators may have been unable to reach these households, or household members may have refused participation. In several cases, we excluded survey data where the head of household was underage. Additionally, sample selection for the household survey was based on our original matching algorithm, which matched beacons to households by identifying the closest household to the point of maximum signal strength for each beacon sighting. However, we later updated our matching algorithm at the analysis stage to reflect the procedures described above. There are therefore occasionally households identified as containing lanterns under the new algorithm but not under the old algorithm. Such households may not appear in our survey data as households containing lanterns; in practice, they account for 44% of 150 matched households for which we lack survey data. However, some such households happened to be randomly selected for the survey ($n = 20$ under the basic match criterion); these households were originally selected as "control" units (i.e., households in which lanterns were not detected), but we include them in our analyses as matched households. In cases where we identified the household as containing a lantern under the old algorithm but not under the new algorithm ($n = 17$), we exclude these households from our analyses. These households were not randomly selected, so their inclusion would undermine the representativeness of unmatched (i.e., "control") households.

decisions. We also collected information about ownership of solar lanterns to validate the inferences made via the tracking technology.[13]

2.1 Ethical issues

Before turning to our findings, it is important to briefly discuss the ethical concerns raised by using iBeacon technology to track the distribution of development goods, and the steps we took to address these concerns.As previously explained, beacons transmit a signal with a unique identifier. While they collect and transmit no other information (for example, they do not record conversations), recipients of the tagged lanterns might feel that we violated their privacy and autonomy if they learned that they received lantern containing devices that could make the lanterns' locations known. Village elders might feel similarly harmed if they learned that we were tracking the lanterns we asked them to distribute without their knowledge—particularly if our tracking revealed malfeasance and if the residents of their village became aware of this finding. In addition to these individual-level harms, the distrust generated by such reactions might "poison the well," undermining future efforts by outsiders to distribute welfare-improving development goods in these communities, thus undermining the communities' welfare more broadly. Along similar lines, backlash could also impair future research efforts. Fully informing the village elders and lantern recipients that the lanterns contained tracking devices would solve the problem, but it would likely alter the distribution behavior that we aimed to measure.[14]

Our approach was to inform the village elders that 10% of the lanterns we were distributing in our project contained tracking devices.[15] This statement was true: although all of the 244 lanterns distributed in the study villages contained beacons, we distributed an additional 2,250 solar lanterns that did not contain tracking devices elsewhere in the same county. In addition, every lantern distributed in the main

[13]The questions about lantern ownership were embedded within a module of questions about ownership of other household assets so as not to draw attention to our interest in solar lanterns and to maintain the firewall between the malaria study (discussed in Section 2.1) and the lantern distribution project.

[14]For useful discussions of the challenge of balancing full disclosure with maintaining the validity of research findings, see Baele (2013), Humphreys (2015) and Hoffmann (2020).

[15]The full text of the instructions the village elders received is available in Appendix C. Village elders also signed a receipt indicating that they had received the solar lanterns and reaffirming their understanding about the potential for tracking. The receipt clarified that participation in the project was entirely voluntary and stated that project organizers might later return to confirm that the solar lanterns remained within the village and that village elders might or might not be notified if this monitoring occurred. Our protocols also dictated the provision of untagged lanterns should any village elder make that request, although none did.

study villages contained a label indicating in the local language that it might contain a tracking device and providing a phone number to contact with questions. Thus lantern recipients were at least minimally informed of potential tracking despite lack of direct contact with any study personnel. In designing these features of the project, our goal was to strike a balance between providing full information (recognizing that doing so would almost certainly alter the village elders' distribution behavior) and being completely deceptive about our research objectives.[16]

Prior to the project launch, we conducted a series of focus groups in villages close to our study area during which we fully disclosed our intention to tag and track solar lanterns in order to learn whether village elders misallocated them. Some focus groups included village elders, while others deliberately excluded them to empower participants to express honest opinions even if they contradicted the village elder. The strong endorsement of our plans by the focus group participants (driven in large part by the expectation that village elders *would* misallocate the lanterns and that it would be useful to document such malfeasant behavior), along with the absence of objections on grounds of privacy, deception, or inadequate disclosure of our research aims, served as a form of community (Anderson and Spellecy, 2020) or inferred/surrogate (Humphreys, 2015) consent for our use of the tracking technology.[17] We also consulted widely on our project design, incorporating critical feedback from multiple seminar audiences in both Kenya and elsewhere.[18]

In addition to concerns related to the use of the tracking devices, ethical concerns may also arise from the requirement that our field officers repeatedly come within 20 meters of every building in the study villages. Residents may perceive such periodic visits in close proximity to their homes as violations of privacy and might become suspicions about what the field officers were doing in the villages—perhaps revealing that the lantern distribution was being monitored and thus changing the behavior we sought to study. Our approach was to embed the tracking missions within a parallel research project aimed at assessing malaria risk. This project was in fact real: we recorded the presence of standing water in the vicinity of every building; collected information on malaria knowledge and exposure, relevant behaviors, and social networks through which health-related information might be usefully disseminated; and are preparing a formal report

[16]We reflect further on the difficulty of threading this needle in our companion paper (anonymized version available here).

[17]We interpreted the findings from these focus groups as confirmation that it was unlikely "that engaged individuals would withhold consent if fully informed consent were sought," per APSA (2020) Principles and Guidance for Human Subjects Research, "Deception."

[18]We are thankful for critical feedback from seminar participants at the University of Nairobi, Strathmore University, the Cape Town meeting of the Working Group in African Political Economy, the Evidence in Governance and Politics network, and the East Africa Social Science Translation Summit.

of our findings that will be shared with village elders and local health officials. Given the high prevalence and negative health impacts of malaria in our study area (Were, 2019), the malaria risk assessment project provides a real benefit for our study communities—while also providing a rationale for the mapping of village buildings, the tracking missions, and the household survey. This element of the research design may reasonably qualify as deceptive: we omitted links between the malaria project and the iBeacon tracking during the consent processes for the former.[19] However, as noted above, the village elders were informed (and acknowledged in the documents they signed when they received the lanterns) that we might monitor the lantern distribution without notification.

We also undertook measures to protect our research participants from potential harms stemming from the release of our research findings. For example, we were concerned that village residents might react negatively if our tracking data revealed that their village elder had misallocated the solar lanterns. To prevent this situation from occurring, all data collection was blind. We designed our tracking app not to reveal when it detected beacons over the course of the tracking missions, so field officers had no way of knowing whether a building they visited contained a tagged lantern. We also designed the application to upload the data it collected directly to a remote server, viewable only by the PIs. Finally, we committed in advance not to identify the study villages or the specific county in which we worked, and only to report aggregate results.

3 Does the Technology Work?

Previous efforts to use remote sensing technology to track development goods have had only limited success. For example, a study employing passive, radio frequency identification (RFID) tags to take inventories of goods held by microenterprises in Sri Lanka was able to detect only about one-quarter of the tagged items on average, with high variability in day-to-day success (de Mel et al., 2016). The iBeacon technology, which relies on active rather than passive tags, performed much better—despite the more challenging tracking task we were asking of it. In contrast to the Sri Lanka study, where the location of the goods was known and fixed within each microenterprise, we had no idea where in each village the tagged lanterns might be located. Yet we were able to detect 98.8% of them in at least one of the five tracking rounds, 80.3% across all five rounds, and 94% across four out of five. We detected at least 90% of beacons in each tracking round, with no discernible trend toward declining performance over time. Moreover, inventories of all 244 lanterns

[19]To keep the lantern and malaria surveillance projects separate, we employed distinct research teams for each component. Staff were fully aware of the projects' connections and expressed no objections.

taken prior to distribution (to confirm that the tags were working) took less than two minutes. In the Sri Lanka study, reading the tags was time consuming, with 10-15 minutes necessary to take inventories of the approximately 280 items that each retail firm held (de Mel et al., 2016).

Beyond detecting the presence of tagged items, iBeacon technology also offers the promise of identifying the particular households in which the items are located. This presents an enormous opportunity for learning about how goods are distributed, with important implications for both policy and theory. Identifying specific recipients of the tagged items is, however, a more challenging task than simply determining whether the items are present somewhere in the study area. Although the protocols described earlier for matching detected beacons to households are straightforward in principle, their application in practice was sometimes imperfect. As shown in Appendix E, the difference in signal strength across the best and second best matches was sometimes not very large, thus creating ambiguity regarding which building contained the beacon[20] Poor cell coverage in some areas during the mapping exercise also led to inaccurate building geocoordiantes in some cases, creating the potential for incorrect matching inferences.[21] This problem occasionally caused ambiguity when integrating the survey and lantern tracking data (for further discussion, see Appendix E). For these reasons, we undertake the analyses that follow with multiple datasets, each employing slightly different match standards and data quality controls (see Appendix G for explanations of the differences in the match criteria and data quality controls). In the discussion below, we focus on the subset of results whose strength and robustness across multiple specifications give us confidence in their validity.

To ascertain how well the iBeacon technology performed in matching tagged lanterns to households, we estimate both Type I and Type II error rates. A Type I error occurs when we match a tagged lantern to a household but the household does not report owning a lantern in the survey. We can calculate such errors with some precision because we attempted to interview every household in which a lantern was ever detected. Column 1 of Table 1 shows Type I error rates across all households matched during the final tracking round, the round closest to the survey, where the likelihood is highest that a detected lantern is still in the household.[22] Type I error rates range from about 9% under our most restrictive data quality controls to about 15% under our standard data quality controls. If we restrict our analyses to households matched across at least three rounds (second column)—in other words, matches we were able to make more

[20] Note that this challenge that would be magnified in settings with greater housing density.

[21] Note that this is not a weakness of the iBeacon technology *per se.* Future projects can avoid this problem either by using mapping applications that pre-download maps for manual pin placement or by automatically (rather than manually) dropping pins based on field officer location.

[22] As shown below, we find evidence that lanterns sometimes moved across households over time.

consistently—Type I error rates range from 6% to 11%. Among households matched in at least three tracking rounds, one of which was the final round (third column), Type I error rates range from about 6% to 12%.

Table 1: Type I Error Rates for Matching Tagged Lanterns to Households (Percent)

Data quality controls	Matched in final tracking round	Matched in ≥ 3 tracking rounds	Matched in final & ≥ 3 tracking rounds
Standard	15.4	11.1	12.3
Most restrictive	8.7	5.7	5.9

Note: For analyses using alternative data quality controls, see Table A5 in Appendix H.

A Type II error occurs when we fail to match a tagged lantern to a household but the household nonetheless reports owning a lantern. Estimating Type II error rates is more challenging because households may report owning lanterns that were not distributed during our project. Indeed, of the 55% of households that reported owning at least one solar lantern, nearly half reported having owned their oldest lantern for at least six months, implying that they had acquired one prior to our distribution. We therefore restrict our analysis to households in which we can confirm that the reported lantern had been acquired during the preceding six months. This approach may exclude some households that owned both project lanterns and older, non-project lanterns, and it may include some households with recently acquired lanterns that the project did not distribute. The approach does, however, exclude *some* lantern-owning households that definitely did not acquire their lantern from the project.[23] Under these specifications, the Type II error rate is about 11%, irrespective of the data quality controls employed (see Table 2). Taken alongside the results presented in Table 1, they again suggest that the technology did a good job of correctly identifying households containing tagged lanterns.

Another aspect of the iBeacon technology's performance that can be evaluated is its ability to follow the movement of tagged lanterns across households over time—something difficult or impossible to do with prior approaches to tracking but potentially extremely valuable for learning about intra-household trade and, applied more broadly, the operation of markets and patronage systems. A challenge in studying such

[23] In calculating the Type II error rate, we use our most permissive match criteria (i.e., we include households in which a lantern was detected in any round). Because shifting to a more restrictive match criteria involves recoding "matched" households about which we are less certain as "unmatched," it is likely to induce substantial upward bias in the error rate by overrepresenting households that we wrongly reclassified as "unmatched" but that did in fact receive a lantern, and that therefore report owning one. This overrepresentation is impactful because we have only a small sample of households never matched under our algorithm in the denominator of the Type II error calculation. For these reasons, we view these estimates as more uncertain than the estimates for the Type I error rates.

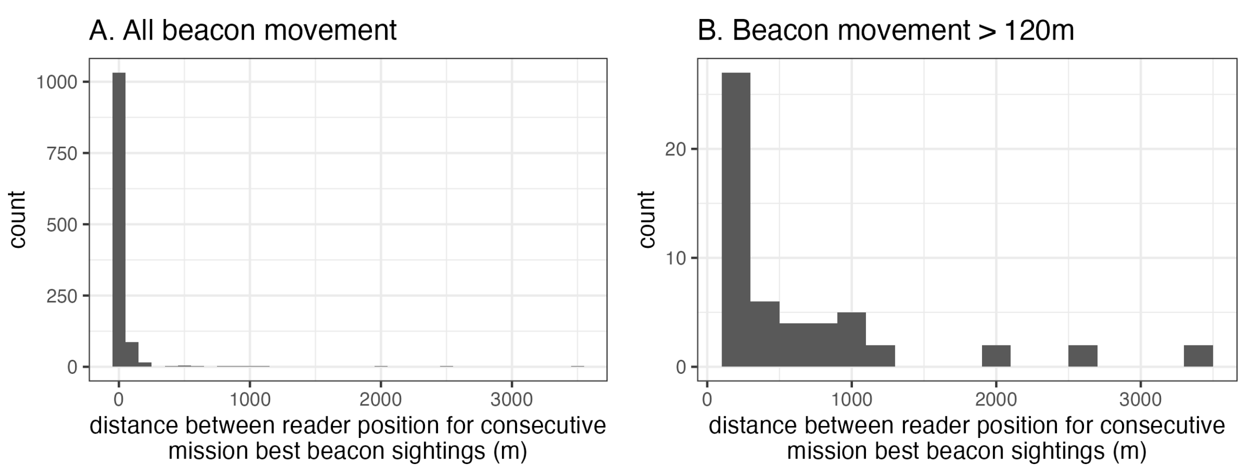
Table 2: Estimated Type II Error Rates for Matching Tagged Lanterns to Households

Data quality controls	Matched in any round
Standard	11.3
Most restrictive	10.5

Note: Analysis only includes households in which we can confirm recent lantern acquisition. For analyses using alternative data quality controls, see Table A6 in Appendix H.

movement is distinguishing between real movement and measurement error. Although the majority of beacons "moved" across tracking rounds (in the sense that the reader's location at the point of highest signal strength for that beacon was not precisely the same across rounds), the median distance between consecutive sightings for any given beacon was just 5.5 meters. As shown in Panel A of Figure 3, the distribution of these "movements" is highly skewed. The vast majority are so small that they very likely reflect measurement error rather than the actual movement of lanterns across households. While most beacon movements were small, 35 of the 244 beacons (approximately 15% of the beacons that we detected) moved more than 120 meters across tracking rounds, and in some cases did so more than once (see Panel B of Figure 3). Because we measure such movements based on distances between the readers' positions in each tracking round and because the maximum distance at which a beacon's signal can be detected is 60 meters, 120 meters is a conservative threshold above which we can be fairly certain of true movement across households, rather than simply measurement error. Figure 4 depicts three snapshots of our study area, showing examples of such cross-household movement.

Figure 3: Distribution of Beacon Movement Across Tracking Rounds.



Panel A shows the distribution of all beacon movement from consecutive beacon sightings; Panel B limits the distribution to beacon movement of > 120 m.

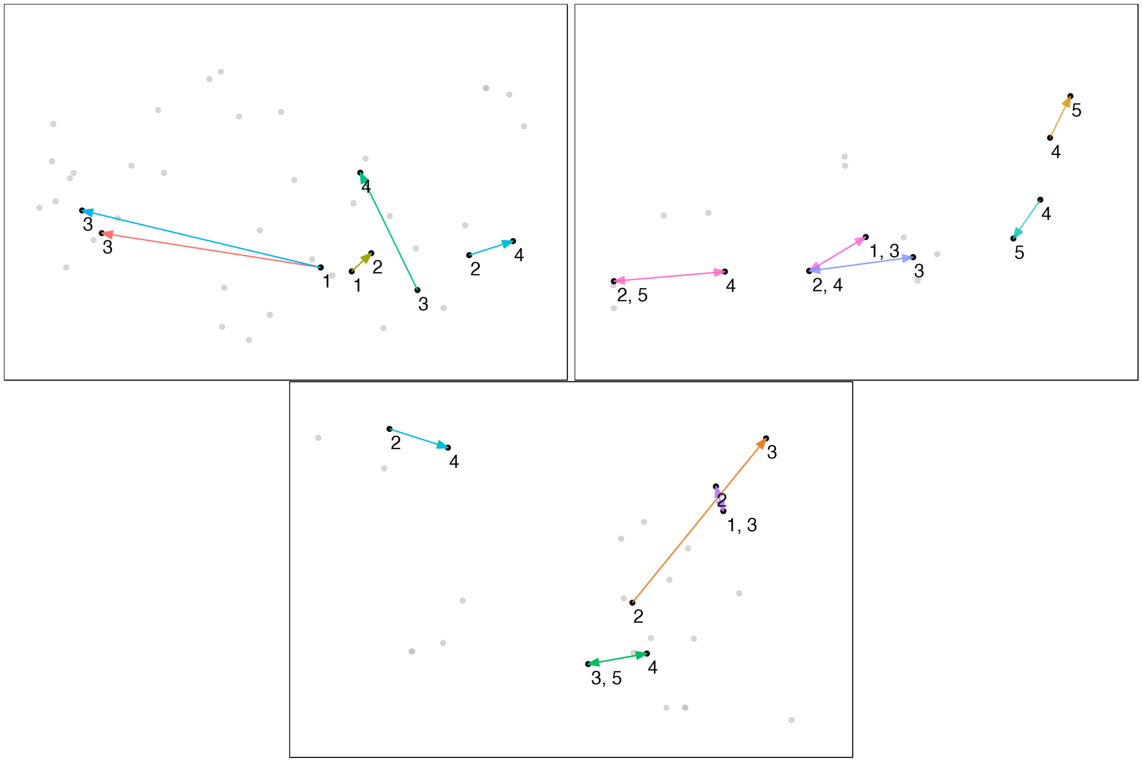


Figure 4: Beacon Movement Across the Five Tracking Rounds (Snapshots)

Grey dots indicate first-round locations of beacons that were stable or "moved" less than 120 meters across consecutive tracking rounds. Black dots indicate the locations of beacons that moved more than 120 meters (i.e., likely true movement) in consecutive sightings, with arrows showing the direction of movement. Numbers indicate the round in which the moving beacon was detected in each location.

4 What Did We Learn About How the Lanterns Were Distributed in Our Study Area?

Within our study context, deviation from program guidelines can occur in two ways. First, because we asked each village elder to distribute the lanterns within their own community, deviations can occur if lanterns exit the community—either to another study village or out of the study area entirely. In either case, the lanterns are not reaching their intended recipients. Contrary to expectations, we find almost no evidence of leakage of this first kind. Second, as we asked village elders to prioritize households with children under five, deviations from program guidelines can occur if recipient households include no children below that age. While we do find evidence of some leakage of this second type, it is less than anticipated—and follows patterns at odds with prevailing assumptions in the development literature about the behavior of local elites.

4.1 Leakage out of villages

As noted, less than 2 percent of the tagged lanterns we distributed (just 3 of 244) were never detected in any of the five tracking rounds. We were able to detect such a high share of the beacons both because the tracking technology worked well and because almost none of the tagged lanterns leaked out of the study villages. In addition, the vast majority of lanterns (over 98% in each round) were detected in the village in which they were distributed. These patterns were not what the conventional wisdom about leakage that motivated our study led us to expect.[24] They were also not what local experts anticipated we would find. In a prediction survey administered to Kenyan researchers and policymakers with significant experience on development issues, the median expectation was that 45% of the lanterns would leak out of the study villages.[25]

One concern is that the low rate of leakage out of the study communities might have been due to the warnings delivered to the village elders that the lanterns might contain tracking devices. In our effort to balance the ethical requirement that we inform village elders about the possibility of tracking against the danger of altering their behavior, it is possible that we erred too far in the former direction and that village elders, understanding that their behavior was being monitored, went out of their way to follow program guidelines to the letter. To evaluate this possibility, we took advantage of the 2,250 untagged solar lanterns that we distributed outside of our main study sites. We distributed these additional lanterns in two different sub-counties located within the same county as the main study. In one, we followed the identical protocols as in our main study sites: the lanterns carried labels indicating that they might contain tracking devices, and we informed village elders about the possibility of lantern tracking. In the other, we provided no such information or labels.

Some period after we delivered the untagged lanterns to the village elders, field officers visited 24 of the villages in each of the two areas to see if they could track down where the lanterns had gone. The objective was to mimic the sort of post-hoc audit that often occurs after the distribution of development goods in a typical aid program. The field officers began by asking the village elders which households had received the lanterns. They then visited each household (in many cases consulting lists that the village elders had kept without our prompting) to confirm whether or not the household had in fact received a lantern. The visits took place in two waves, with roughly half occurring 3-4 weeks after the lantern distribution and the other half occurring 6-7 weeks after. In all, the field officers visited 1,129 households across the 48 villages.

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[24] Indeed, in anticipation of the lanterns leaking out of the study villages and potentially being resold at local markets, we arranged for our field officers to visit the main markets closest to our research sites to see if the tracking app detected any project lanterns for sale. Sweeps conducted after the first and fourth tracking rounds detected no tagged lanterns in the markets.

[25] Further information about the prediction survey is provided in Appendix D.

Although lanterns were slightly more likely to be found in villages where the village elder was told that the lanterns might be tracked, the difference across the two areas was very small and not statistically significant. If knowledge about the possibility of tracking altered the behavior of the village elders, it appears to have done so only minimally. Evidence from interviews conducted with participating village elders after the project's conclusion supports this conclusion. When asked explicitly whether they thought the lanterns they distributed might have contained tracking devices, only a quarter said yes (although nearly half mentioned the tracking devices at some point during the wide-ranging interviews). When asked whether this possibility affected the way they distributed the lanterns, none answered in the affirmative. We think it is thus reasonable to conclude that informing the village elders that the lanterns might be tagged cannot account for the surprisingly low leakage rates.

4.2 Leakage within villages

Given the instructions village elders received about which households to prioritize, a first question is whether households in which we detected a beacon (i.e., "lantern households") always contained children under five. Table 3 shows a confusion matrix reflecting whether a beacon was detected in a household versus whether the household contained at least one child under five. Among the 250 lantern households for which we have survey data, 153 (61.2%) met this main eligibility criterion.[26] These averages mask substantial variation across villages, with the share of lantern households that contained children under five ranging from roughly 40% to as high as 80%.[27] We are hesitant to interpret these figures strictly as "leakage rates" for two reasons. First, village elders' distribution decisions may not account for whether or not a beacon was detected in a household.[28] Second, we are missing survey data for 37.5% of the households that received lanterns. However, even if we cannot treat these figures strictly as "leakage rates," the patterns in Table 3 do suggest that factors other than the requested prioritization shaped distribution decisions.

Village elders might reasonably have targeted households without children under age five if every

[26]The figures presented in Table 3 are coded using basic match criteria and standard data quality controls. As we show in Appendix I, the share of lantern households with children under five ranges from roughly 61% to roughly 69% under alternative match criteria and data quality controls. There are more lantern households than lanterns because, as described earlier, some lanterns were detected in multiple households.

[27]Both low power and a commitment, discussed in Section 2.1, to report only aggregate findings prevent us from further exploring this cross-village variation.

[28]As noted, and discussed further in Section 4.4, lanterns sometimes moved across households over time. The implied "leakage rate" is lower if we restrict beacon sightings to the first tracking round (see Appendix I).

Table 3: Confusion Matrix: Lantern Possession versus Eligibility

At least one child under 5	Beacon detected Yes	No
Yes	153	91
No	97	211
Total	250	302

Note: This analysis employs basic match criteria and standard data quality controls.

household meeting this criterion had already received a lantern; however, the second column of Table 3 shows that dozens of households met the priority criterion yet did not receive lanterns. Thus, a shortage of eligible households does not explain the deviation from program guidelines.

4.3 Patterns of (mis-)allocation

What else may have shaped distribution patterns? We first consider whether households that did not meet the priority criterion of having a child under five but that nevertheless received a lantern (i.e, "ineligible recipient households") had any characteristics distinguishing them from non-recipient households (see Table 4). This comparison, which contrasts households in the bottom left cell of Table 3 with those in the right column, offers insight into the factors beyond program eligibility that might account for the village elders' allocation decisions. Table 4 reflects our basic match criteria and standard data quality controls, but the discussion that follows also reflects results under alternative specifications, as reported in Appendix J.1.

In the first panel, we consider household composition. Beyond not having children under five—a definitional artifact of ineligibility—ineligible households that received lanterns were more likely to have at least one primary school-aged child (i.e., above 5 but still of school age), at least one retirement age (60+) adult, and to consist exclusively of retired adults. These differences, all of which are indicative of need for a solar lantern,[29] are consistent across specifications, but only occasionally attain marginal significance.

In the second panel, we consider broader need-based household characteristics that might explain receiving a lantern, including the availability of alternative lighting sources and socioeconomic status. We find that ineligible recipient households had less access to alternative lighting: in particular, they were 10 percentage points less likely to have grid connections, a difference attaining marginal statistical significance

[29]Solar lanterns are especially valuable in households with primary school-aged children because the lanterns make it possible to do schoolwork after dark (older secondary school students often attend boarding schools). Elderly household members also find solar lanterns especially useful for visiting the latrine at night.

in some specifications. We also find that ineligible recipient households experienced more lived poverty than non-recipient households—a difference that is consistent across specifications and often statistically significant. The housing quality index also attains marginal statistical significance, but the sign and significance are highly unstable across specifications.

Table 4: Difference-in-Means Between Non-Recipient and Ineligible Recipient Households

	Overall mean	No beacon detected	Ineligible households w beacon detected	Difference	Std. error	Total n
Household composition						
Child under 5 (binary)	0.23	0.30	0.00	-0.30***	0.05	393
Children under 5 (count)	0.29	0.39	0.00	-0.39***	0.07	393
Child between 5 and 12	0.51	0.50	0.55	0.05	0.06	393
Retired adult	0.33	0.30	0.41	0.11*	0.05	393
Only retired adults	0.06	0.05	0.08	0.03	0.03	393
Household size	4.13	4.16	4.05	-0.11	0.27	393
Alternative need-based characteristics						
Already owns lantern	0.24	0.25	0.22	-0.04	0.05	393
Connected to electric grid	0.19	0.21	0.11	-0.10*	0.05	393
Owns solar home system	0.70	0.71	0.67	-0.04	0.05	393
Assets index (village standardized)	-0.01	0.00	-0.06	-0.06	0.11	393
Housing quality index (village standardized)	0.07	0.00	0.30	0.30*	0.14	376
Lived poverty index (village standardized)	0.07	0.00	0.29	0.29*	0.12	387
Relationship with village elder						
VE is immediate family member	0.25	0.24	0.31	0.07	0.05	381
VE is extended family member	0.33	0.31	0.40	0.09	0.06	381
VE is related	0.39	0.36	0.47	0.11	0.06	381
Spoke w VE in past week	0.44	0.40	0.56	0.17**	0.06	381
Shared meal w VE in past week	0.08	0.07	0.09	0.02	0.03	381
Worships at same church as VE	0.04	0.03	0.05	0.02	0.02	351
VE connections index (village standardized)	0.05	0.00	0.22	0.22	0.13	351

Note: Two sample t-test with pooled variance. We constructed the asset, housing quality, lived poverty, and village elder connections indices by extracting the first principal component from principal component analyses including relevant variables for all households with available data pooled across villages, such that item rotations for the first principal component are consistently in the expected direction; we then standardized these variables within each village. We count a parent, child, brother, or sister as immediate family; an aunt, uncle, niece, nephew, or cousin as extended family. See Appendix F for additional details. The analysis presented here employs our basic match criterion: a household is coded as having a beacon detected within it if our matching algorithm ever produced this household as a match in any round. For replications of the analysis using alternative match criteria and data quality controls, see Appendix J.1. *p<0.5; **p<0.01; ***p<0.001

Given the focus in the African politics literature on parochial favoritism (Burgess et al., 2015; Kramon and Posner, 2016; Hodler and Raschky, 2014; De Luca et al., 2018), we were also interested in whether recipient households had stronger social ties to village elders. In the the third panel of Table 4, we investigate several measures of such ties: whether the village elder was an immediate family member, an extended family member, or related in some more distant way; whether members of the household had spoken to or shared a meal with the village elder during the past week; and whether household members and the village elder worship at the same church. We also combined these measures by extracting a single principal component, subsequently standardized by village, to capture their joint impact. Ineligible households that received lanterns were indeed more likely to have more social connections to the village elder. This difference is always significant for speaking with the village elder, and sometimes significant for familial connections and the combined index. While this finding would seem to validate the expectation that personal favoritism guided lantern distribution, the strongest result (speaking with the village elder) may indicate a post-treatment effect: receiving a lantern, for whatever reason, initiates a relationship with the village elder that results in a greater likelihood of recent conversation. In contrast, measures of stronger social connection (familial relations) have weaker, albeit consistently positive, effects.

Because many more households contained children under five than village elders were given lanterns to distribute, village elders had to make choices about which eligible households to select. What additional factors did they consider? Table 5 compares recipient to non-recipient households among households meeting the main distribution criterion (corresponding to the top row in Table 3). As above, Table 5 reflects our basic match criteria and standard data quality controls, but our discussion also reflects results under alternative specifications, as reported in Appendix J.2.

The first panel again considers household composition. Recipient households were more likely to have primary school-aged children and to have more members than non-recipient households, which may enable more individuals to share the benefits of having a solar lantern. These differences are consistent across specifications and sometimes statistically significant.

The second panel considers alternative need-based criteria that might motivate village elders to select some eligible households over others. Households with children under five that received lanterns were less often connected to the electricity grid, a difference that is consistent across specifications and sometimes marginally significant. Recipient households also consistently had lower quality housing (sometimes significant) and experienced greater lived poverty (always significant).

Finally, the third panel again considers whether eligible households that received lanterns had stronger social connections to the village elder. The patterns are similar but weaker than the findings from Table 4: households receiving lanterns had stronger social ties on average to the village elder; however, the only indicator to ever achieve statistical significance is speaking with the village elder within the last week. We interpret these results as weak suggestive evidence that social connections played at least some role in the village elders' allocation decisions.

These analyses only consider one household characteristic at a time. Ideally, we would employ multiple regression to account for many factors simultaneously. We did fit regression models using household characteristics to predict lantern receipt; these analyses are available in Appendix K. Results are generally consistent with the patterns noted above: lack of grid connection, lived poverty, and having spoken with the village elder significantly and consistently predict receiving a lantern, with other indicators sometimes reaching significance. However, these models explain, at best, only approximately one quarter of variation

Table 5: Difference-in-Means Between Eligible Non-Recipient and Eligible Recipient Households

	Overall mean	Eligible households, no beacon detected	Eligible households, beacon detected	Difference	Std. error	Total n
Household composition						
Child under 5 (binary)	1.00	1.00	1.00	0.00	NA	243
Children under 5 (count)	1.27	1.28	1.27	-0.01	0.07	243
Child between 5 and 12	0.68	0.58	0.74	0.16**	0.06	243
Retired adult	0.14	0.16	0.12	-0.03	0.05	243
Only retired adults	0.00	0.00	0.00	0.00	NA	243
Household size	5.56	5.17	5.78	0.62*	0.28	243
Alternative need-based characteristics						
Already owns lantern	0.21	0.24	0.19	-0.05	0.05	243
Connected to electric grid	0.14	0.17	0.12	-0.05	0.05	243
Owns solar home system	0.70	0.68	0.71	0.03	0.06	243
Assets index (village standardized)	-0.11	-0.01	-0.16	-0.15	0.12	243
Housing quality index (village standardized)	-0.30	-0.20	-0.36	-0.16	0.11	230
Lived poverty index (village standardized)	0.27	-0.06	0.47	0.53***	0.15	242
Relationship with village elder						
VE is immediate family member	0.19	0.16	0.21	0.05	0.05	236
VE is extended family member	0.27	0.22	0.29	0.07	0.06	236
VE is related	0.33	0.28	0.36	0.09	0.06	236
Spoke w VE in past week	0.47	0.32	0.56	0.24***	0.07	236
Shared meal w VE in past week	0.09	0.07	0.10	0.04	0.04	236
Worships at same church as VE	0.05	0.04	0.06	0.02	0.03	213
VE connections index (village standardized)	-0.06	-0.19	0.02	0.21	0.14	220

Note: See notes to Table 4. For replications of the analysis using alternative match criteria and data quality controls, see Appendix J.2. *p<0.5; **p<0.01; ***p<0.001

in which households received lanterns, reflecting the significant complexity underlying the village elders' allocation decisions. Unfortunately, the small scope of our pilot precludes full exploitation of possible analyses under a regression framework to capture this complexity. For example, interacting household characteristics with eligibility would allow us to understand whether other characteristics mattered conditionally, and a random effects analysis could help to capture variation in distribution patterns across village elders. We anticipate that future studies using iBeacon technology at scale will have adequate power to undertake and profit from such analyses.

Notwithstanding our small sample size, our findings point to some clear and persistent trends. Beyond having a child under five, several alternative indicators of need seem to have meaningfully shaped lantern distribution patterns in our study villages: notably, lanterns often ended up in households lacking electric connections and experiencing lived poverty. These findings suggest that village elders weighed their own knowledge of household need alongside the stated program prioritization. Even though we did not mention these other indicators of need as priorities (or even secondary considerations) in our distribution instructions, village elders appear to have employed them as guidelines in making their allocation decisions. We also find at least some suggestive evidence that social connections to the village elder may have affected whether or not households received lanterns, especially among ineligible households.

4.4 Second-order allocation

Our ability to track beacon movement over time allows us to study not just the allocation decisions of the village elders but also the reallocation decisions of the households that received the lanterns. As noted earlier, we found that roughly 15% of lanterns likely moved across households during the five rounds of tracking missions. Although this figure is a potentially conservative estimate of actual cross-household lantern movement,[30] it is still less than trade theory might have led us to expect if the original recipients were poorly chosen target recipients. We interpret this as one more piece of evidence that the village elders leveraged local knowledge to make sure that the lanterns were given to households that needed them.

Because we collected household survey data from every household in which a beacon was ever matched in any tracking round, we are in principle in a position to compare the characteristics of households that transferred and received lanterns during the course of such second-order allocations. However, because roughly half of the cases of cross-household lantern movement involve "round trip" movements from one household to another and back again across tracking rounds (as illustrated in Figure 4), the already small

[30] As discussed in Section 3, we limit our analysis to beacons that moved more than 120 meters, whose movement we can be fairly confident was across households.

number of movements in which we can contrast the characteristics of the sending and receiving households becomes smaller still. It is perhaps not surprising, then, that we find no significant differences in the characteristics of sending and receiving households—including whether the receiving household reported having paid for the lantern it possessed.

An alternative approach to learning about the how lanterns moved after their initial distribution is to compare the characteristics of households in which beacons were detected in our first and fifth tracking rounds. In the first tracking round, which occurred within a week after the village elders received the lanterns, we can more confidently attribute the presence of a lantern in a household to the village elder's allocation decision. In the fifth, lantern location also captures the process of household to household reallocation that took place over the ensuing eight weeks. Table 6 compares households matched in Round 1 but not Round 5 to those matched in Round 5 but not Round 1.[31] The same analyses under alternative data quality controls appear in Appendix J.3.[32] None of these results are statistically significant, reflecting the smaller sample size in this analysis. Nonetheless, they are suggestive. The prevalence of having a child under five, the variable that captures the household characteristic that we asked village elders to prioritize, is higher in Round 1 than in Round 5. Other indicators of need, however, become more prominent over time. For example, having a primary school-aged child, lacking grid access, lived poverty, and lower quality housing are all more common among lantern households in Round 5.[33] These differences are all consistent with the redistribution of lanterns from original recipient households to households with greater need. We also see that the relationship with the village elder is weaker among households with lanterns detected in Round 5 than in Round 1, consistent with the influence of such connections in shaping village elders' initial allocations and the presence of villagers with greater need outside of the village elders' families.

5 Rethinking "leakage"

We motivated this paper by presenting the leakage of development goods as a problem. The common perspective in the academic and policy literatures is that deviations from program guidelines constitute

[31]The "round trip" movement of lanterns noted earlier, which suggests borrowing or sharing across households, is necessarily excluded from these analyses.

[32]The validity of these comparisons would be undermined by significant decay in beacon detection rates across tracking rounds—for example due to leakage of lanterns outside of the study villages over time or because the beacons became inoperative. However, as shown in Table A3 of Appendix B, beacon detection rates are quite constant across tracking rounds, so this is not a concern for the analysis here.

[33]The difference in housing quality does actually attain significance in some alternative specifications; see Appendix J.3.

Table 6: Difference-in-Means Across R1 Match versus R5 Match Households

	R1 Match mean	R1 match households (n)	R5 match mean	R5 match households (n)	Difference	Std. error
Household composition						
Child under 5 (binary)	0.63	52	0.53	49	0.10	0.10
Children under 5 (count)	0.77	52	0.65	49	0.12	0.14
Child between 5 and 12	0.60	52	0.67	49	-0.08	0.10
Retired adult	0.23	52	0.18	49	0.05	0.08
Only retired adults	0.02	52	0.04	49	-0.02	0.03
Household size	5.10	52	4.86	49	0.24	0.41
Alternative need-based characteristics						
Already owns lantern	0.23	52	0.24	49	-0.01	0.09
Connected to electric grid	0.13	52	0.08	49	0.05	0.06
Owns solar home system	0.67	52	0.63	49	0.04	0.10
Assets index (village standardized)	-0.04	52	0.03	49	-0.06	0.18
Housing quality index (village standardized)	0.16	50	-0.21	45	0.38	0.27
Lived poverty index (village standardized)	0.19	51	0.57	49	-0.37	0.22
Relationship with village elder						
VE is immediate family member	0.26	47	0.13	47	0.13	0.08
VE is extended family member	0.30	47	0.21	47	0.09	0.09
VE is related	0.40	47	0.28	47	0.13	0.10
Spoke w VE in past week	0.62	47	0.47	47	0.15	0.10
Shared meal w VE in past week	0.15	47	0.04	47	0.11	0.06
Worships at same church as VE	0.07	44	0.05	42	0.02	0.05
VE connections index (village standardized)	-0.01	49	-0.29	44	0.29	0.19

Note: See notes to Table 4. For replications of the analysis using alternative match criteria and data quality controls, see Appendix J.3. *p<0.05; **p<0.01; ***p<0.001

evidence of malfeasance or corruption—or, at the very least, undermine aid efficiency. While relatively small in terms of sample size, our application of iBeacon technology to the tracking of solar lanterns within off-grid communities in western Kenya illustrates this technology's potential to learn about leakage and empirically examine our assumptions about this phenomenon.

Contrary to both the conventional wisdom and the predictions of local experts, we find that lanterns very rarely, if ever, leaked outside of our study area. Village elders in fact distributed lanterns throughout their communities. This pattern alone limits the potential for substantial welfare losses owing to leakage. Most residents in these communities have relatively low socioeconomic status. For example, only one dozen of the 552 households in our sample own a refrigerator. Even among non-lantern households (which experienced lower rates of lived poverty), most households reported some level of food insecurity. As highlighted earlier, the median household has unmet needs for electric household lighting. Thus even as some households may need solar lanterns more than others, potential welfare losses from misallocation within the community are relatively small.[34]

We chose a priority criterion that we reasonably thought would maximize potential welfare gains. We find that the village elders usually adhered to the priority criterion in choosing beneficiaries, but not always.

[34] For similar arguments, see Alatas et al. (2013).

While theft and diversion of development goods surely is an issue in some contexts, our findings suggest that a pair of more innocuous—and potentially even *welfare-enhancing*—explanations may be at work when goods do not wind up where their donors intended.

First, distributors may leverage local knowledge to target needy recipients whether or not they meet official eligibility criteria. We find evidence that not only the presence of young children, but also poverty, grid access, and the presence of additional, older children who could use lanterns for completing schoolwork may have shaped village elders' distribution decisions. Our program guidelines had a strong and defensible rationale: the kerosene lanterns that are commonly used in Kenya for lighting after dark in off-grid communities are especially dangerous for young children (Lam et al., 2012). But, like the guidelines imposed in most donor projects, they captured only one dimension of hardship. Distributors may know that eligible households are not equally needy; they may also know that certain ineligible households are particularly needy on dimensions not well-captured in the stated eligibility guidelines. Our findings are consistent with village elders drawing on their own local knowledge about who would benefit most from the solar lanterns and deviating from program guidelines where they felt it was necessary to help households that our program guidelines would have excluded.[35] For example, in our post-survey, several village elders recounted instances in which they gave lanterns to households that did not have young children but that contained elderly residents. In a strict definitional sense, such deviations are leakage. But they have the intention, and effect, of improving the welfare of people in the community.

The village elders' behavior in this regard is in keeping with the behavior of local elites charged with distributing development goods in other studies (Honig, 2020). Basurto, Dupas and Robinson (2020) find that chiefs in Malawi use their informational advantages to direct subsidies to people who need it most, even when they fail to qualify via proxy means testing. In an audit of a subsidized bed net distribution program using confederates posing as would be recipients, Dizon-Ross, Dupas, and Robinson (2017) find that health workers were willing to bend the rules to give bed nets to particularly needy applicants with small children, even if they failed to meet the program guidelines—a phenomenon they term "benevolent leakage." These findings, and ours, suggest that the application of local knowledge to channel development goods to needy recipients who would otherwise have not received them is an underappreciated source of what is commonly

[35]Anticipating the desire of village elders to deviate in some instances from the instruction to prioritize lantern distribution to households containing children under five, and not wanting them to feel they were violating our trust if they did, we were careful to present our distribution guidelines as a *prioritization* rather than a requirement. In our post-survey, several village elders expressed appreciation for this leeway, explicitly contrasting our instructions with the instructions provided in other development projects in which they were given lists of pre-selected beneficiaries, some of whom they felt should not have been included.

labeled as "leakage."

Second, original program recipients may redistribute goods based on better information about needs. Instances of "leakage" may also occur when development goods are discovered in the hands of people who do not meet program criteria but who obtained the goods from qualifying recipients. Our analysis of lantern movement identified several instances of such second-order allocation. Assuming that the exchanges behind such movements are voluntary, we can infer that they are welfare improving for both the original recipient and the new owner. Both parties are made better off, even while the location of the good in a household that may not meet program criteria appears in the data as a case of "misallocation." Anecdotally, this practice of recipient re-allocation or resource pooling is common, drawing attention recently in part owing to its potential to undermine the internal validity of randomized control trials.[36] While potentially at odds with researchers' and aid providers' intentions, second-order allocation is not antithetical to social well-being.

All of these deviations from program guidelines are technically "leakage." But they have the effect of improving, not undermining, community welfare—an implication strongly at odds with the equation of leakage in the popular media and some academic writings with malfeasance and ineffectiveness.

One explanation for the divergence between our findings and expectations could be that some important feature makes the context we studied relatively unusual. Notably, aid and research projects occur with great frequency in our study region, and the village elders whom these projects invariably call upon to act as go-betweens may know that bad reputations will deter beneficial future projects. In such a context, even the small possibility that aid providers could become aware of malfeasant behavior may have been enough to dissuade village elders from diverting the lanterns for private ends—a consideration likely heightened by village elders' embeddedness within the communities they serve (Tsai, 2007; Gottlieb, 2017; Magaloni, Díaz-Cayeros and Ruiz Euler, 2019; Baldwin, 2013). If our study site was atypical, then deployments of iBeacon technology to other settings will allow researchers and practitioners to update, and potentially qualify, the implications of the results reported here.

Another possible explanation is that, thanks to the technology we employ, our study is measuring a different kind of deviation from program guidelines, or deviations occurring at a different level, from most other studies. Most of the headline-grabbing leakage in Kenya and elsewhere involves contract fraud, bid-rigging, kickbacks, and other kinds of financial fraud (*Nation* (Kenya), 2018, 2024) rather than the type of leakage we focus on here. Even if we limit our focus to the misallocation of physical goods that governments and donors distribute, most of the leakage may occur during the procurement process and in the initial stages of distribution (for example, as the goods are traveling between the port or production

[36] For examples, see de Sardan and Hamani (2018); Kinstler (2024); Blattman (2022).

facility and the local warehouse or supply depot), with relatively less leakage occurring at the final stage when goods are distributed to their intended recipients by local officials embedded within their own communities. Employing technologies like iBeacon makes it possible to study this crucial, previously black-boxed last stage of the distribution process, and, accordingly, to deepen our understanding of how and when leakage occurs.

6 Conclusion

Current approaches to measuring the leakage of development goods fall short. Both perception-based surveys and comparisons of goods allocated versus received provide estimates of what may have gone missing, but tell us little about when in the distribution process the goods may have been diverted or where they went. This shortcoming leaves researchers and policymakers with a weak empirical grasp of how leakage operates and whom it benefits—and thus little leverage to test key observable implications of theories about aid effectiveness, and how goods flow through markets. It also makes it challenging to distinguish between actual malfeasance and deviations from program guidelines that have the intention and effect of targeting needy but otherwise excluded recipients.

In this paper, we introduce and pilot the use of iBeacon technology to address these weaknesses. Our evidence demonstrates that the technology can be a powerful tool for detecting the presence of development goods distributed in a real world setting and for tracking their movement over time. iBeacon technology represents a substantial improvement over previous iterations of similar technologies in this respect, operating extremely reliably in a field setting. This performance enabled us to develop some early findings regarding patterns of leakage. While a small sample size restricted our ability to explore the full scope of possible analyses, our hope is that this pilot represents the first step in a new research agenda that leverages the this technology's potential to learn about how development goods are distributed, when they go missing, and why.

The promise of iBeacon technology for this purpose does not, however, mean that it will work in all settings or for all applications. First, not all development goods are amenable to tagging. While researchers and distributors can feasibly place iBeacon tags within lanterns, cook stoves, computers, bicycles, and other durable goods that donors and governments regularly distribute, they cannot tag cash, whose distribution has become a favored means of aiding poor communities (Leisering, 2018). Other commonly distributed goods like relief food, fertilizer, or pharmaceuticals also present a problem, but for a different reason: the taggable item is the bag or the carton that the good comes in rather than the good itself. When these containers become separated from the quantity of interest, as they often do in the course of their distribution, it becomes challenging to identify the end recipient or to track the container's movement over time.[37] Beacons are also incapable of detecting the siphoning off of some of the bag's contents en route to its destination—a common form of theft (*Herald* (Zimbabwe), 2020). When medical supplies are distributed from central warehouses, they can be feasibly tracked as they make their way to regional health facilities, as in the pioneering study by Jablonski et al. (2023). But the tracking breaks down at the last stage of the distribution process when the cartons containing the tracking devices are unpacked for sale at local clinics and pharmacies—and this stage is where much of the misallocation and diversion occurs (*Daily Monitor* (Uganda), 2017). iBeacon technology works best for tracking durable and non-divisible goods.

Second, the applicability of the technology depends on the setting in which the goods are distributed. For beacons to be detectable, members of the research team need to be able to come within 20 meters of every location in which a tagged item might be located. The locations also cannot be so spread out that tracking missions become infeasible or, conversely, too densely situated, lest it be challenging or impossible to identify the buildings from which the signals are emanating. Unlike GPS, this technology's application for tracking purposes requires inference, and contextual features shape the user's ability to make and confidence in those inferences.

Finally, while iBeacon tags are cheaper than alternatives like GPS tags, the cost of tagging every item during large-scale distributions would be prohibitive for the kinds of low value goods—relief food, bed nets, farming inputs—that are ordinarily distributed in aid and development projects. Tracking goods distributed over broader areas would also increase implementation costs. The technology will therefore likely be most useful for quickly verifying the presence of high-value goods (e.g., laptops in schools or medical equipment in clinics) distributed in well-defined settings. It will also be valuable for research projects seeking to learn about which method(s) of distribution are most efficient and welfare-enhancing, the findings of which can then be applied to improve the effectiveness of development programming. While these conditions limit the applicability of the technology, they still leave a wide range of applications for which iBeacon technology can be a useful tool for studying leakage and the distribution (and movement) of development goods. Furthermore, these limitations may diminish as the underlying technology evolves.[38]

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[37] For example, when a family receives a bag of maize, it is often transferred to a storage receptacle and the bag is discarded or repurposed, potentially winding up in another household.

[38] In our own project, the cost of designing and purchasing the beacons, developing the software, mapping the households in each community, and executing the five rounds of tracking missions totaled approximately $60,000 (see Appendix A.3 for a breakdown). However, roughly three-quarters of this cost was for software and hardware development—expenses that would not be borne by future projects, which can take advantage of our investment in creating these tools. Furthermore, marginal costs will drop in applications with a larger scope, and as prices fall over time. For example, the beacons used in our project

In addition to generating insights into how development goods are distributed in a real setting, our study also provided an opportunity to think hard about how to deploy iBeacon technology ethically. Researchers and practitioners who are excited about the potential learning that can come from employing iBeacon and similar remote sensing technologies will need to design their studies in a way that balances the payoffs from being able to track where tagged items go alongside the privacy and autonomy of the people and communities they are studying.

cost $15 each. Today, that price has dropped to $10, and scaling up the number of units from 250 to 2,000 would reduce the cost to about $8 per beacon.

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7 Appendices

A Further details on iBeacon technology

iBeacon technology is a Bluetooth-based tracking technology that relies on two components: uniquely identifiable tags (beacons) and a reader (in our case, an iPhone). Beacons transmit a signal that readers can detect. Readers collect data on any detectable beacons that are in range. In plain terms, a beacon continuously “shouts its name” so that any nearby reader might “hear” it. A reader records the “name” of any beacon(s) it “hears,” along with other data. Figure A1 shows one of the beacons employed in this project.

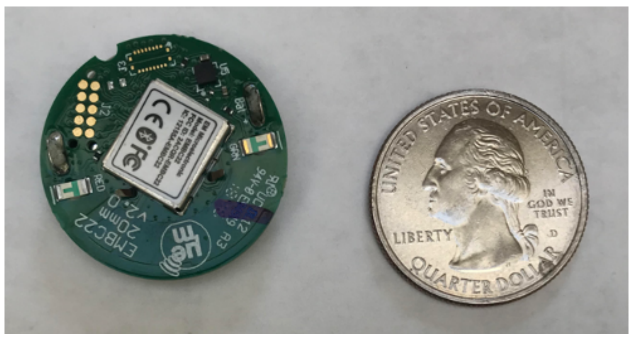

Figure A1: An iBeacon

A.1 Comparison to other tracking technologies

iBeacon tags are similar to active RFID tags insofar as they contain a power source (a battery) and actively transmit signals; these features allow for greater signal range. Unlike traditional RFID technologies, iBeacon operates with the standard Bluetooth Low Energy iBeacon protocol and does not require a specialized reader. Any iOS or Android device can serve as a reader using its Bluetooth capabilities and an appropriate reading application. Unlike GPS technology, iBeacon technology does not involve triangulation and therefore cannot give the precise location of tags. Instead, readers merely record whether any beacon signals are detectable. Commercially available iBeacon technology like Apple AirTags and Tile trackers, which consumers often use to track objects like keys or luggage, confidentially leverage many smartphone users as reading devices, allowing tracking even when the beacon owner’s phone is not in proximity to the beacon. This process can increase the effective range of iBeacon tags. While more limited in terms of precisely locating tags, iBeacon tags is considerably cheaper than GPS tags. A GPS tracker may cost \$100 and last for 1 week. An iBeacon tag could cost less than \$10 and last for 2 years.

A.2 Beacon range

The effective range of an iBeacon varies depending on several factors:

- **Beacon characteristics:** Different iBeacon hardware has different advertising capabilities. In addition, manufacturers may program beacons to have more or less signal transmission power depending on the size of the battery and desired lifetime of the beacon. For instance, manufacturers determine how frequently and how "loudly" beacons advertise their presence. Our beacons are programmed to maximize signal transmission power and to transmit once per second, limiting the lifetime of the beacon's battery to about six months.

- **Reader characteristics:** Like beacons, readers can have different abilities to detect bacons either because of hardware or manufacturer programming. For instance, iPhones check for beacon signals approximately once per second. Additionally, newer mobile phones are equipped with more sensitive antennas to receive Bluetooth signals; an older phone may not be able to "hear" the signal from a distant beacon while a newer phone could. We employ an iPhone 7 and an iPhone 8 as readers in this project.

- **Environmental factors:** Some materials interfere with signals more than others; for instance, chain link fences and liquids in particular can diminish the range of the beacons.

Considering these factors, there is no guaranteed range at which a reader can detect a beacon. Nonetheless, users may be able to define an upper limit to the range for a particular beacon-reader combination. In our case, this maximum line-of-sight range is about 100 meters. However, in real-world applications with obstacles and non-optional antenna alignment, 20-60 meters is a more realistic expectation.

A.3 Cost of deploying the technology

The cost of deploying the iBeacon technology in the context of our research design was the sum of four different costs: 1) the cost of the mapping exercise at the outset of the project; 2) the cost of developing the software and procuring and fine tuning the beacons; 3) the cost of conducting the tracking missions; and 4) the cost of the household survey. The fourth cost would be common to alternative, shoe leather approaches to monitoring. The main additional costs unique to employing iBeacon technology are for the mapping exercise, the software and hardware, and the tracking missions. In our project, these expenses totaled approximately \$60k, with roughly \$48k spent on the contract with Geocene, the firm we engaged to develop the software and purchase and fine tune the beacons for our purposes, roughly \$9k spent on the tracking missions, and roughly \$3k spent on the mapping exercise (see Table A1).

Table A1: Expenses associated with using iBeacon technology in our research design

Budget category	Total cost	Cost per unit	Notes
Mapping exercise	\$3,000	∼\$1 per structure	∼12 villages; 2,824 structures
Software/hardware development	\$45,000		Fixed cost that future projects can avoid
Beacons	\$3,750	\$15 per beacon	Cost will diminish significantly at scale
Tracking missions	\$9,000	∼\$150 per village/round	Cost will depend on village sizes

Note: The table enumerates expenses associated with employing iBeacon technology in our project. Other expenses such as purchasing the items that were tagged and conducting the household survey would be common to tracking efforts using traditional survey-based tracking approaches, and are excluded.

While these costs are illustrative, the cost of employing iBeacon technology in other applications will depend on the project scale. Projects with larger numbers of tagged items can realize reductions in per-unit hardware costs. For example, while beacons today cost about \$10 per unit for orders of 250 units, they drop to \$8 per unit for orders of 2,000 units, \$6.50 for orders of 20,000 units and \$5 for orders of 200,000 units.

Projects in which tagged goods need to be tracked over larger areas will entail higher expenses associated with the mapping and tracking. Audit-style use of beacons—for example, checking that medical hardware is in a clinic or that laptops are in a school—would entail lower personnel costs because the geographic coverage is more focused.

B Details of the tracking missions

B.1 Data collection during the tracking missions

We worked with Geocene to develop a customized beacon scanning app for the tracking missions. The app completely automates data collection, minimizing opportunities for human error. In addition, the app blinds enumerators to the data collected, thus minimizing risks to both participating communities and enumerators. The user interface is minimal, consisting of three options: (1) "Start" data collection, (2) "Stop" data collection, and (3) "Sync" data to our cloud-based server. Figure A2 shows screen shots of the application.

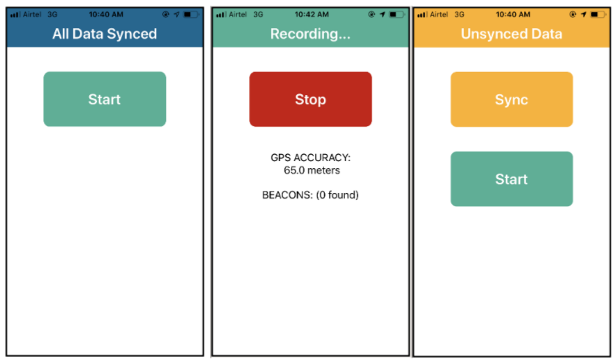

Figure A2: Reading Application Interface

When a user initiates data collection, the application automatically records data at one-second intervals until the user stops data collection. Data is collected regardless of whether the reader detects any beacons. Data collection does not rely on the availability of a cell coverage. The data collected include the following:

- **Mission ID**: A mission is a single instance of data collection. It begins when a user presses "Start" and ends when the user presses "Stop." Mission IDs are universally unique identifiers (UUIDs).
- **Timestamp, latitude, and longitude of the reader**: These data allow us to track the routes the field officers took during their tracking missions. During the course of data collection, we used these data to confirm that the field officers came within 20 meters of every building during their missions. In the analysis phase of the project, we used these data to match found beacons to households, as described in the paper.
- **Beacon identifying information**: In raw form, a beacon's identity consists of three elements: a UUID, a major code, and a minor code. The UUID is the same for all beacons employed in our

project. This UUID is how the reading application "listens" only to beacons associated with our project (and not, for example, beacons from other manufacturers for other applications). The major and minor codes are five digits each. The major and minor code together create an identifier unique to each individual beacon within the project.

- **Received signal strength indicator (RSSI)**: The RSSI is basically an indicator of how well the iPhone can "hear" the beacon. The RSSI takes values ranging from about -30dB to -90dB. These values are exponents, so numbers closer to zero indicate stronger signals.

The collected data is stored locally on the iPhone until the field officer secures internet access. At this point, the field officer can manually sync data to our cloud-based server. It is never possible to access the collected data through the iPhone application—only through Periscope, an online, password-protected platform that is only accessible to the PIs. From Periscope, the PI's can download several types of data files, including files that track the path of the iPhone during the tracking mission (where the unit of observation is the mission-second) and beacon sightings files (where the unit of observation is an in-range beacon second). These latter files allow us to track the approximate location and RSSI of sighted beacons, which allow us to match sighted beacons households, as described in the paper. Periscope also has an integrated mapping function, as illustrated in Figure 1.

B.2 Some statistics from the tracking missions

We instructed field officers to come within 20 meters of every building in each village during their tracking rounds. The mean mission building coverage rate at 20 meters was 90.75% (median = 94.4%). The distribution of this coverage rate is shown in Figure A3.

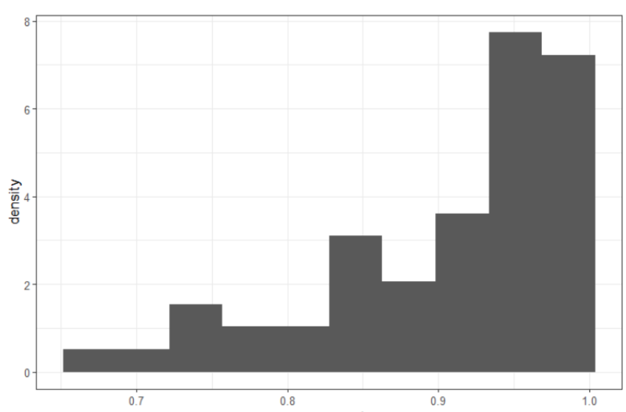

Figure A3: Coverage Rate at 20 Meters by Village-Round (All Buildings)

Although 20 meters is the conservative distance at which a beacon signal should be detectable, beacons should also be detectable at a distance of 30 meters under most circumstances. The mean mission building coverage rate at 3om was 96.9% (median = 93.5%). The distribution is shown in Figure A4

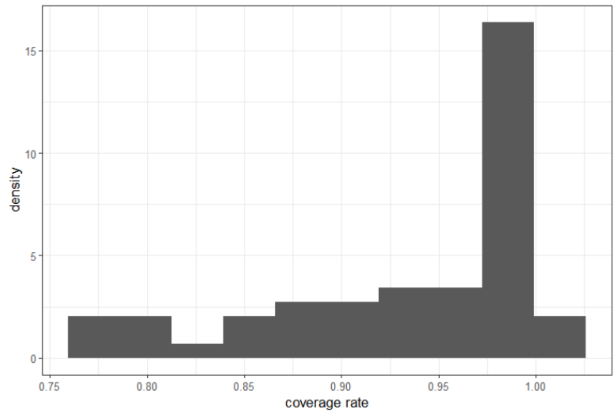

Figure A4: Coverage Rate at 30 Meters by Village-Round (All Buildings)

There was some variation in the coverage rates across rounds, but no clear trend:

Table A2: Coverage Rate Across Tracking Rounds

	Mean coverage rate at 20m	Mean coverage rate at 30m
Round 1	96.1	97.7
Round 2	84.9	89.8
Round 3	89.7	92.2
Round 4	91.4	93.8
Round 5	92.1	94.3

Households may have been missed because occupants asked them not to approach, because they were fenced and inaccessible, because adverse whether cut tracking missions short, or because of human error.

As reported in the paper, we were able to detect 98.8% of the beacons in at least one tracking round. The distribution of detection rates across tracking rounds was as follows:

Table A3: Detection Rate Across Tracking Rounds

	Percentage of beacons detected
Round	95.9
Round 2	93.4
Round 3	92.6
Round 4	94.2
Round 5	91.0

C Information provided to village elders

C.1 Instructions to village elders for distributing the lanterns

We are here as part of the Lighting Kenya Project. In this project, we are distributing solar lanterns to several sub-locations in [redacted] County. We chose this sub-location specifically because we know there is a particularly great need here for lighting after dark.

We want to make sure that the lanterns we distribute remain in the villages in which we distribute them. We have placed tracking devices in some of the lanterns we are distributing and plan to use them to confirm that the lanterns remain where they are supposed to be. The tracking devices only reveal the approximate locations of the lanterns but do not collect any other information. For example, they do not record conversations.

For budget reasons, we are not able to put the tracking devices in all of the lanterns we are distributing. Only 10% of the lanterns we are distributing in [redacted] County have tracking devices. This means that for every lantern that contains a tracking device, there are nine that do not. The lanterns we give you may or may not contain tracking devices.

This is what the solar lanterns look like. [Hold up a lantern and demonstrate its function.] As you will notice, the lantern contains a label explaining that it may contain a tracking device. Again, for budget reasons we were not able to put the tracking devices in all the lanterns that we are distributing in [redacted] County. Only one out of every ten lanterns has such a device.

We have prepared boxes of lanterns for each village elder. The box you will receive contains a number of lanterns determined by the size of your village. Larger villages will receive more lanterns, and smaller villages will receive fewer. We ask that you only distribute the solar lanterns you receive within your own village.

We are eager for people in this area to benefit from the lanterns we are distributing, so we request that you distribute them in your villages within one week.

While we recognize that many people in your villages would benefit from receiving a solar lantern, we request that the first priority be households with children under five years old. These young children may require help during the night, and tin lamps present a danger for their health and safety. The smoke from tin or kerosene lamps are especially harmful to the health of children. In addition, young children may not understand the danger of tin or kerosene lamps, so they are more likely to knock them over. This can result in fire or burns. Solar lanterns can help prevent these accidents.

Thank you in advance for your participation in the Lighting Kenya Project.

C.2 Receipt/Consent Form

Acknowledgement of Receipt of Solar Lanterns

I acknowledge having received X solar lanterns from the Lighting Kenya Project, which I agree to distribute within my village within one week.

I understand that the project organizers may return later to confirm that the solar lanterns remained within the village, and that I may or may not be notified if they do.

I also understand that tracking devices have been placed in 10% of the solar lanterns that are being distributed in [the project area] and that the purpose of the tracking devices is to confirm that the solar lanterns remain where they are supposed to be.

I also understand that I have been requested to prioritize distributing the solar lanterns to households with children under five years old, as young children may require help during the night and tin lamps present a danger for their health and safety.

I understand that my participation in this project is entirely voluntary.

I acknowledge receipt of a card with information about who to contact if I have any questions, comments or concerns about the Lighting Kenya Project.

Signature:

Date:

D Prediction survey

To better understand whether our findings regarding leakage and misallocation were surprising, we collected information about the predictions of local experts in Kenya. During seminar presentations to the economics and development departments at the University of Nairobi, Kenyatta University, and Strathmore University, and at a lunch presentation at the Busara Center for Behavioral Economics, we paused our talk after we had explained the details of the project but before we revealed what we had found. Before continuing with our presentation, we administered a brief survey asking seminar participants to indicate their expectations about leakage (what share of the 244 lanterns we are distributing do you think are likely remain in the study villages?) and deviations from program guidelines (what share of lanterns do you think were found in households containing at least one child under 5 years old?).

We collected surveys from 70 seminar participants, who, on average, had 4.5 years of experience studying/working on development issues. The median prediction for the share of lanterns that would remain in the study villages was 55% (mean = 62%). The median prediction for the share of lanterns that would be found in households meeting the primary program criterion (i.e., containing children under five) was 65% (mean = 57%). The distribution of predictions are displayed in Figure A5 below. We do not highlight the results about expected deviations from program guidelines in the paper because of ambiguity about whether the respondents were responding in terms of the total number of lanterns that were distributed or from among the lanterns they predicted would remain in the study villages.

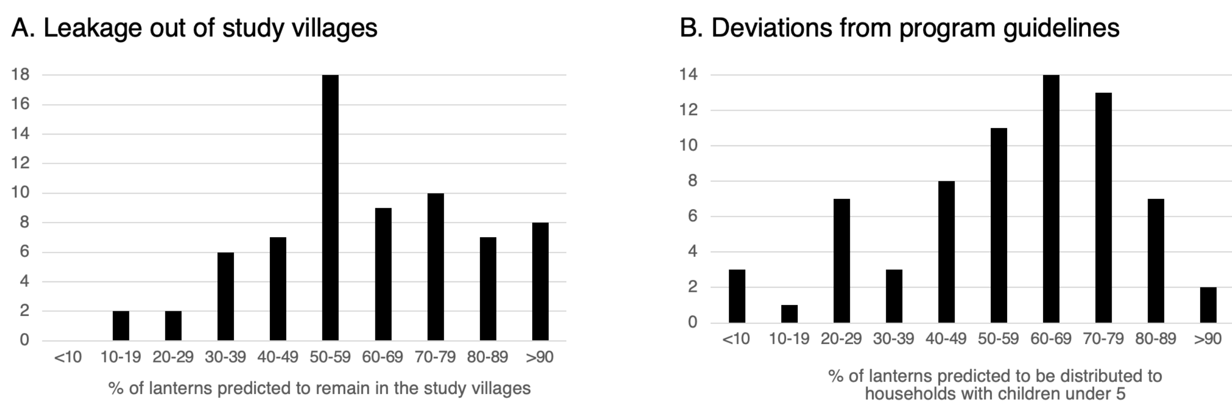

Figure A5: Predictions About Leakage and Misallocation

Panel A shows the distribution of predictions about the share of lanterns that would remain in the study villages; Panel B shows the distribution of predictions of the share of lanterns that would be found in households containing at least one child under 5 years old.

E From tracking data to distribution inferences: Processes and complications

E.1 Matching found beacons to households

In matching found beacons to buildings, one of the complications highlighted in the paper is that beacons were sometimes detected in the vicinity of multiple buildings.[39] In 73.4% of match cases, the beacon was detected near more than one building belonging to distinct complexes. As shown in Figure A6, the modal case (26.6% of cases) is a beacon detected near two buildings from different complexes during the same mission. This case slightly edges out unambiguous cases where the beacon was sighted near only one building (27.2% of cases).

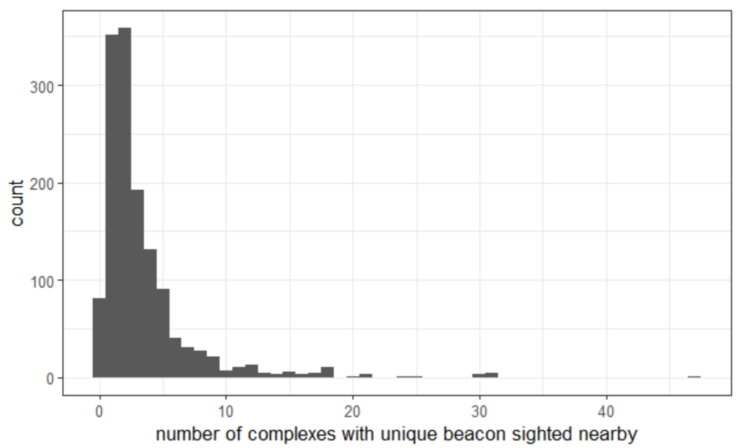

Figure A6: Distribution of Potential Number of Matches per Sighting

Detecting a beacon in proximity to multiple buildings is not necessarily a problem for matching if there is a significant differential in the beacon's signal strength detected in proximity to each building. Among cases where beacons were detected near multiple complexes, the mean difference in linear signal strength between the best building match and the second-best building match of a distinct complex is 12.2 (median = 9.8). Figure A7 shows the full distribution of these differences.

[39] In the vicinity of or near means that on the tracking path points closest to the building, the reader detected a beacon. Complexes refer to grouped sets of buildings belonging to the same household or institution. For example, we might detect a beacon near a main dwelling as well as near a kitchen *of the same household complex.* These figures reflect matches to different buildings belonging to distinct complexes, e.g., kitchens for two different households.

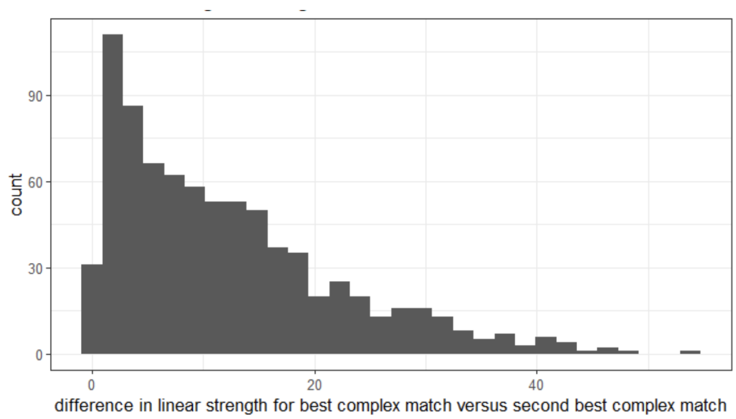

Figure A7: Distribution of Signal Strength Differentials.

E.2 Merging tracking data with the household survey data

Several complications also arose when merging tracking data with survey data. First and foremost, buildings lacked unique identifiers. During the initial mapping exercise, field officers had to manually create building labels and accidentally, unintentionally used some building labels twice. In addition, field officers also encountered difficulties accurately recording building locations during the mapping exercise because of poor cell coverage, which later caused problems during the household survey. During the survey, we provided survey enumerators with the coordinates of the target household. However, enumerators sometimes arrived at this location only to find themselves between multiple houses. When ambiguous cases like this occurred, enumerators interviewed both households and recorded both sets of answers under the same household label. Thus, duplicate labels occurred in both tracking data (arising from labeling errors during the mapping exercise) and during the survey (arising from inaccurate household coordinates). Labels thus cannot serve as unique identifiers for merging these data sets. Geo-coordinates are an alternative potential unique identifier, and we employed them as such when processing tracking information and inferring matches. Yet while survey tablets recorded the interview location, these coordinates usually did not precisely match the originally recorded household location. Thus, geo-coordinates cannot serve as unique identifiers to merge tracking and survey data.

These difficulties generated four case types when merging tracking and survey data, displayed in Table A4. For ambiguous cases (case types 2 through 4), we resolved cases using the tracking-to-survey data assignment that minimized discrepancy in distances between the mapping/tracking coordinates and the interview coordinates. For case type 3, we discarded the extra survey data for the discrepant household since it inclusion would undermine the integrity of sample construction: unmatched households are representative only if they are randomly selected, and these households were not randomly selected.

Table A4: Summary of Merge Resolution Cases

Case type	Duplicated in intended sample	Duplicated in survey	Number of cases	Number of retained cases	Of retained cases...		
					Number of matched cases	Number of unmatched cases	Number of consequential resolutions
1	no	no	545	531	293	238	NA
2	no	yes	9	8	5	3	0
3	yes	no	15	13	7	6	0
4	yes	yes	4 (2 pairs)	2	2	0	0

We also investigated whether these resolutions were consequential to the confusion matrix of inferred versus reported lantern ownership. For example, imagine a survey enumerator arrived at (inaccurately recorded) household geocoordinates only to find herself between two households. She interviews both households and records them under under the same label. During the interview, one household reported owning a lantern and one did not. Tracking data indicate the household under this label possessed a lantern. In this example, picking one household versus the other would be consequential to the confusion matrix: our inferences about lantern ownership from tracking data could be confirmed or contradicted by reported ownership, but the evaluation depends on how we resolve the case. Conversely, if neither or both households reported owning a lantern, it would not be consequential; our tracking-based inference would either always be confirmed or always be contradicted by reported ownership. While some consequential resolutions occurred, they were dropped due to other restrictions. We are confident that resolution decisions from ambiguous cases (case types 2 to 4) does not undermine findings because we also conduct robustness tests using only case type 1 data (see Appendix J).

Finally, we dropped household interviews from our data set if they met one of the following conditions:

- *The recorded household label was not in the intended sample.* In this case, the enumerators likely interviewed an intended household by made a mistake when entering the household label. We considered attempting to reassign these cases to an "un-interviewed" household from the intended sample, but there were often multiple candidates that were off by a single digit. Reassignment thus seemed as likely to produce error as accurate resolution. This rule eliminates 6 households.
- *The household was non-randomly selected for the sample but is not a matched household under the improved algorithm.* Our analyses are based on an improved algorithm, while our sample selection occurred under the original algorithm. Some households that generated a match under the original algorithm did not generate a match under the improved algorithm. Although we do not think these households have a lantern, we cannot use them as part of our non-lantern control group. They were not randomly selected and will therefore undermine the representativeness of that group. This rule eliminates 17 households.
- *The interviewee was under 18 years old.* These individuals should not have been interviewed under our research plan and ethical approvals, so we do not use the resulting data. This rule eliminates 3 households.

We are then left with a total of 566 interviews, 251 of which are matched under our improved tracking algorithm and 305 of which are both (pseudo-)randomly selected and not matched under our improved algorithm.[40]

F Index construction

The asset, housing quality, and lived poverty indices are constructed from the following components:

- The **asset index** includes items on the number of cookers/gas stoves, refrigerators, radios, televisions, computers, DVD players, mobile phones, sofas, sewing machines, water tanks, wood/metallic beds, chairs, tables, cars/trucks, motorcycles, bicycles, and animal drawn carts owned in total by members of the household. We exclude an item on bank accounts owing to missing data and an item on boats owing to an unexpected rotation on the first principal component. The first principal component captures 60.80% of variation across these items.
- The **housing quality index** includes items regarding acres of land accessible for household use, the number of rooms in the house, whether the walls are made of stone, brick or cement, whether the roof is concrete or corrugated iron, whether the floor is cement, tile, or laminate, the location of the water source, the time it takes to retrieve water, the type of toilet, and the location of the toilet. The first principal component captures 61.84% of variation across these items.
- The components of the **lived poverty index** include how often in the past month the household has gone without enough food to eat, without enough fuel to cook, or without medicine or medical treatment because they could not afford it. The first principal component captures 71.54% of variation across these items.
- The **VE connections index** includes a familial closeness variable, constructed as an ordinal composite of whether the VE is immediate family (3), the VE is extended family (2), and whether VE is otherwise somehow related (1); whether someone in the household has spoken with the VE in the past week; whether someone in the household has shared a meal with the VE in the past week; and whether the household worships at the same institution as the VE. The first principal component captures 83.2% of variation across these items. We lack data on the VE's institution of worship in one village, so we also construct a secondary VE connections index for some analyses which excludes shared worship institutions. In this case, the first principal component captures 85.0% of variation across included items.

[40] It is not perfect random selection because those 17 houses that were antiquated matches from the original algorithm should have been eligible for random selection but were not. We cannot correct this problem post-hoc.

G Defining data quality controls

The main results presented throughout this paper assume that survey enumerators interviewed the household they reported and that the interviewed household represents the target household. We include households in these analyses that had duplicated labels during the census and/or survey exercises, resolving such ambiguities by assigning data to households in a matter that minimizing geographic discrepancies between interview locations and the originally recorded household locations from the census (see Appendix E).

In alternative specifications, we apply different data controls to confirm that main trends hold.

- First, we only include households in the analyses if the most proximate household to the recorded interview location is the target household ($n = 356$). In other words, we exclude a household if the interview purportedly for this household occurred closer to a different household than the target household based on initial mapping exercise coordinates. Although failure to mean this standard does not necessarily indicate that the enumerator went to the wrong household, that is one potential explanation for the discrepancy.
- Second, we only include households in the analyses if the recorded interview location fell within one kilometer of the target household ($n = 548$). Although failure to meet this standard does not necessarily indicate that the enumerator went to the wrong household, this is one potential explanation for the discrepancy.
- Third, we only include households in the analyses if the numeric ID assigned to the household was unique in both the census and the survey data (i.e., case type 1, $n = 528$). We exclude any cases where we used discretion to resolve potentially ambiguous data assignment (see appendix E).
- Fourth, we only include households eligible for inclusion under all the above included criteria ($n = 340$). In other words, we exclude any household that raises identifiable concerns about whether matching and survey data are correctly assigned to households.

Note that all variable construction app lied prior to the application of these various data quality controls (e.g., index construction and standardization). In this respect, the covariates are not robust to data quality controls.

H Error Rates: Robustness to alternative data quality controls and specifications

Table A5: Estimated Type I Error Rates for Matching Tagged Lanterns to Households

Data quality controls	Round 5 match	Confident match	Round 5 & confident match
Standard	15.4	11.1	12.3
Most proximate HH is interviewed HH	10.1	7.8	7.6
Interview within 1km of HH location	14.5	9.5	10.9
Non-duplicates only	15.5	11.2	12.4
Most restrictive	8.7	5.7	5.9

Note: Descriptions of the different data quality controls are provided in Appendix G.

Table A6: Estimated Type II Error Rates for Matching Tagged Lanterns to Households

Data quality controls	Matched in any round
Standard	11.3
Most proximate HH is interviewed HH	10.2
Interview within 1km of HH location	11.3
Non-duplicates only	11.4
Most restrictive	10.5

Note: Descriptions of the different data quality controls are provided in Appendix G.

I Confusion matrix: Robustness to alternative data quality controls and specifications

Table A7: Percentage of Lantern Households with Child under Five

	Match criteria			
Data quality controls	Basic	Confident	Verified	Round 1 (basic)
Standard	61.2	66.0	68.8	65.8
Most proximate HH is interviewed HH	63.0	68.2	66.9	65.9
Interview within 1km of HH location	61.5	66.5	69.1	66.2
Non-duplicates only	62.0	66.0	69.2	66.9
Most restrictive	64.0	68.3	67.1	67.2

Note: For detailed descriptions of alternative data quality controls see Appendices G.

Table A7 demonstrates the robustness of the confusion matrix presented in Table 3 by replicating the analysis reflected in the upper left cell under alternative match criteria (columns) and data quality controls (rows). The first column displays results under our basic match criterion. Here, we code a household as containing a beacon if our algorithm matched a beacon to the household during any of our tracking rounds. In the second column, we limit the set such that it includes a household as a match if and only if the matching algorithm produced this household as a match in at least three of five tracking rounds. In the third column, we limit this set to households that, in addition, confirmed owning a lantern in the household survey.[41] The fourth column considers only basic matches from the initial tracking round. In this case, we are more confident that the village elder is responsible for lantern distribution patterns, as the original lantern recipient had only minimal time to redistribute the lantern. The first row uses standard data quality controls, while latter rows apply more stringent criteria (see Appendix G for additional details).

[41] We do not prefer this survey-verified match criteria because of potential incentives to not report lantern ownership (e.g., if the household did not meet the priority criterion) and because lantern possession may not be constant over time (see Section 4.4).

J Difference-in-means: Robustness to alternative data quality controls and specifications

J.1 Non-recipient versus ineligible recipient households

J.1.1 Alternative Match Criteria

Table A8: Difference-in-means (Confident Matches)

	Survey mean	No beacon detected	Beacon detected	Difference	Std. Error	Total n households
Child under 5 (binary)	0.26	0.30	0.00	-0.30***	0.06	348
Children under 5 (count)	0.33	0.39	0.00	-0.39***	0.09	348
Child between 5 and 12	0.51	0.50	0.60	0.10	0.08	348
Retired adult	0.31	0.30	0.37	0.06	0.07	348
Only retired adults	0.07	0.05	0.13	0.08*	0.04	348
Household size	4.14	4.16	4.02	-0.14	0.34	348
Already owns lantern	0.25	0.25	0.23	-0.02	0.07	348
Connected to electric grid	0.20	0.21	0.12	-0.10	0.06	348
Owns solar home system	0.70	0.71	0.67	-0.04	0.07	348
Assets index (village standardized)	-0.01	0.00	-0.04	-0.04	0.15	348
Housing quality index (village standardized)	0.03	0.00	0.18	0.18	0.16	335
Lived poverty index (village standardized)	0.02	0.00	0.12	0.12	0.15	342
VE is immediate family member	0.26	0.24	0.42	0.18*	0.07	339
VE is extended family member	0.33	0.31	0.47	0.15*	0.08	339
VE is related	0.39	0.36	0.53	0.17*	0.08	339
Spoke w VE in past week	0.43	0.40	0.63	0.23**	0.08	339
Shared meal w VE in past week	0.07	0.07	0.05	-0.03	0.04	339
Worships at same church as VE	0.04	0.03	0.05	0.02	0.03	311
VE connections index (village standardized)	0.05	0.00	0.38	0.38*	0.17	311
VE connections index (excl. church, village standardized)	0.04	0.00	0.35	0.35*	0.16	339

Note: Two sample t-test with pooled variance. *p<0.5; **p<0.01; ***p<0.001

Table A9: Difference-in-means (Verified Matches)

	Survey mean	No beacon detected	Beacon detected	Difference	Std. Error	Total n households
Child under 5 (binary)	0.25	0.30	0.00	-0.30***	0.06	356
Children under 5 (count)	0.32	0.39	0.00	-0.39***	0.09	356
Child between 5 and 12	0.53	0.50	0.67	0.17*	0.07	356
Retired adult	0.32	0.30	0.40	0.10	0.07	356
Only retired adults	0.06	0.05	0.08	0.03	0.03	356
Household size	4.21	4.16	4.47	0.31	0.32	356
Already owns lantern	0.27	0.25	0.35	0.10	0.06	356
Connected to electric grid	0.19	0.21	0.10	-0.11*	0.06	356
Owns solar home system	0.70	0.71	0.65	-0.06	0.07	356
Assets index (village standardized)	0.01	0.00	0.05	0.05	0.14	356
Housing quality index (village standardized)	0.04	0.00	0.24	0.24	0.15	342
Lived poverty index (village standardized)	0.08	0.00	0.45	0.45**	0.14	350
VE is immediate family member	0.25	0.24	0.35	0.11	0.07	345
VE is extended family member	0.33	0.31	0.45	0.13	0.07	345
VE is related	0.39	0.36	0.53	0.17*	0.07	345
Spoke w VE in past week	0.43	0.40	0.61	0.21**	0.08	345
Shared meal w VE in past week	0.07	0.07	0.06	-0.01	0.04	345
Worships at same church as VE	0.04	0.03	0.07	0.03	0.03	317
VE connections index (village standardized)	0.05	0.00	0.37	0.37*	0.16	317
VE connections index (excl. church, village standardized)	0.05	0.00	0.35	0.35*	0.15	345

Note: Two sample t-test with pooled variance. *p<0.05; **p<0.01; ***p<0.001

J.1.2 Alternative Data Quality Controls

Table A10: Difference-in-means (Most proximate household to survey site is interviewed household)

	Survey mean	No beacon detected	Beacon detected	Difference	Std. Error	Total n
Match						
Child between 5 and 12	0.54	0.52	0.59	0.06	0.07	235
Retired adult	0.33	0.28	0.46	0.18**	0.07	235
Only retired adults	0.06	0.05	0.10	0.05	0.03	235
Household size	4.19	4.17	4.23	0.06	0.32	235
Already owns lantern	0.26	0.27	0.23	-0.04	0.06	235
Connected to electric grid	0.15	0.17	0.11	-0.06	0.05	235
Owns solar home system	0.71	0.72	0.69	-0.04	0.06	235
Assets index (village standardized)	-0.06	-0.09	-0.02	0.07	0.12	235
Housing quality index (village standardized)	0.03	-0.03	0.16	0.19	0.17	230
Lived poverty index (village standardized)	0.11	-0.01	0.37	0.38**	0.14	230
VE is immediate family member	0.27	0.25	0.32	0.07	0.07	225
VE is extended family member	0.36	0.34	0.40	0.06	0.07	225
VE is related	0.41	0.38	0.48	0.10	0.07	225
Spoke w VE in past week	0.47	0.42	0.60	0.18*	0.07	225
Shared meal w VE in past week	0.08	0.07	0.08	0.01	0.04	225
Worships at same church as VE	0.03	0.03	0.02	-0.02	0.03	211
VE connections index (village standardized)	0.12	0.07	0.25	0.19	0.16	211
VE connections index (excl. church, village standardized)	0.11	0.06	0.24	0.19	0.16	225
Verified Match						
Child between 5 and 12	0.56	0.52	0.67	0.15	0.08	216
Retired adult	0.31	0.28	0.41	0.13	0.07	216
Only retired adults	0.06	0.05	0.10	0.05	0.04	216
Household size	4.22	4.17	4.39	0.22	0.36	216
Already owns lantern	0.28	0.27	0.31	0.04	0.07	216
Connected to electric grid	0.15	0.17	0.08	-0.09	0.06	216
Owns solar home system	0.70	0.72	0.65	-0.07	0.07	216
Assets index (village standardized)	-0.06	-0.09	0.00	0.09	0.14	216
Housing quality index (village standardized)	0.02	-0.03	0.15	0.18	0.18	211
Lived poverty index (village standardized)	0.10	-0.01	0.44	0.44**	0.16	211
VE is immediate family member	0.26	0.25	0.32	0.07	0.08	206
VE is extended family member	0.35	0.34	0.41	0.08	0.08	206
VE is related	0.40	0.38	0.49	0.11	0.09	206
Spoke w VE in past week	0.46	0.42	0.61	0.19*	0.09	206
Shared meal w VE in past week	0.07	0.07	0.05	-0.02	0.04	206
Worships at same church as VE	0.03	0.03	0.03	-0.01	0.03	192
VE connections index (village standardized)	0.11	0.07	0.31	0.24	0.19	192
VE connections index (excl. church, village standardized)	0.10	0.06	0.29	0.24	0.18	206
Confident Match						
Child between 5 and 12	0.54	0.52	0.61	0.09	0.09	206
Retired adult	0.30	0.28	0.37	0.09	0.08	206
Only retired adults	0.07	0.05	0.15	0.10*	0.04	206
Household size	4.13	4.17	3.98	-0.19	0.39	206
Already owns lantern	0.26	0.27	0.22	-0.05	0.08	206
Connected to electric grid	0.16	0.17	0.10	-0.07	0.06	206
Owns solar home system	0.71	0.72	0.68	-0.04	0.08	206
Assets index (village standardized)	-0.08	-0.09	-0.06	0.03	0.15	206
Housing quality index (village standardized)	-0.02	-0.03	0.01	0.04	0.18	202
Lived poverty index (village standardized)	0.04	-0.01	0.22	0.22	0.17	201
VE is immediate family member	0.28	0.25	0.41	0.16	0.08	199
VE is extended family member	0.36	0.34	0.44	0.10	0.09	199
VE is related	0.40	0.38	0.50	0.12	0.09	199
Spoke w VE in past week	0.47	0.42	0.68	0.25**	0.09	199
Shared meal w VE in past week	0.07	0.07	0.06	-0.01	0.05	199
Worships at same church as VE	0.03	0.03	0.03	0.00	0.03	186
VE connections index (village standardized)	0.11	0.07	0.33	0.27	0.20	186
VE connections index (excl. church, village standardized)	0.10	0.06	0.35	0.29	0.20	199

Note: Two sample t-test with pooled variance. *p<0.5; **p<0.01; ***p<0.001

Table A11: Difference-in-means (Survey occurred within 1km of household locaiton)

	Survey mean	No beacon detected	Beacon detected	Difference	Std. Error	Total n
Match						
Child between 5 and 12	0.51	0.49	0.55	0.06	0.06	389
Retired adult	0.33	0.30	0.42	0.11*	0.06	389
Only retired adults	0.06	0.05	0.08	0.03	0.03	389
Household size	4.12	4.16	4.02	-0.14	0.27	389
Already owns lantern	0.24	0.25	0.21	-0.04	0.05	389
Connected to electric grid	0.19	0.22	0.10	-0.11*	0.05	389
Owns solar home system	0.70	0.71	0.68	-0.04	0.05	389
Assets index (village standardized)	-0.02	0.00	-0.06	-0.06	0.11	389
Housing quality index (village standardized)	0.07	0.00	0.29	0.29*	0.14	372
Lived poverty index (village standardized)	0.07	0.00	0.30	0.31*	0.12	383
VE is immediate family member	0.25	0.24	0.31	0.07	0.05	378
VE is extended family member	0.33	0.31	0.40	0.09	0.06	378
VE is related	0.39	0.36	0.47	0.11	0.06	378
Spoke w VE in past week	0.44	0.40	0.56	0.17**	0.06	378
Shared meal w VE in past week	0.08	0.08	0.09	0.02	0.03	378
Worships at same church as VE	0.04	0.03	0.05	0.02	0.02	350
VE connections index (village standardized)	0.05	0.00	0.22	0.22	0.13	350
VE connections index (excl. church, village standardized)	0.05	0.00	0.22	0.22	0.12	378
Verified Match						
Child between 5 and 12	0.53	0.49	0.68	0.18*	0.07	352
Retired adult	0.32	0.30	0.41	0.10	0.07	352
Only retired adults	0.06	0.05	0.08	0.03	0.03	352
Household size	4.20	4.16	4.42	0.27	0.32	352
Already owns lantern	0.26	0.25	0.34	0.09	0.06	352
Connected to electric grid	0.19	0.22	0.08	-0.13*	0.06	352
Owns solar home system	0.70	0.71	0.66	-0.05	0.07	352
Assets index (village standardized)	0.01	0.00	0.04	0.04	0.14	352
Housing quality index (village standardized)	0.04	0.00	0.23	0.22	0.16	338
Lived poverty index (village standardized)	0.08	0.00	0.47	0.47**	0.15	346
VE is immediate family member	0.25	0.24	0.35	0.11	0.07	342
VE is extended family member	0.33	0.31	0.45	0.13	0.07	342
VE is related	0.39	0.36	0.53	0.17*	0.07	342
Spoke w VE in past week	0.43	0.40	0.61	0.21**	0.08	342
Shared meal w VE in past week	0.07	0.08	0.06	-0.01	0.04	342
Worships at same church as VE	0.04	0.03	0.07	0.03	0.03	316
VE connections index (village standardized)	0.06	0.00	0.37	0.36*	0.16	316
VE connections index (excl. church, village standardized)	0.05	0.00	0.35	0.35*	0.15	342
Confident Match						
Child between 5 and 12	0.51	0.49	0.61	0.11	0.08	344
Retired adult	0.31	0.30	0.37	0.07	0.07	344
Only retired adults	0.07	0.05	0.14	0.08*	0.04	344
Household size	4.13	4.16	3.96	-0.20	0.35	344
Already owns lantern	0.24	0.25	0.22	-0.03	0.07	344
Connected to electric grid	0.20	0.22	0.10	-0.12	0.06	344
Owns solar home system	0.71	0.71	0.69	-0.03	0.07	344
Assets index (village standardized)	-0.01	0.00	-0.04	-0.04	0.15	344
Housing quality index (village standardized)	0.03	0.00	0.16	0.16	0.16	331
Lived poverty index (village standardized)	0.02	0.00	0.14	0.14	0.15	338
VE is immediate family member	0.26	0.24	0.42	0.18*	0.07	336
VE is extended family member	0.33	0.31	0.47	0.15*	0.08	336
VE is related	0.38	0.36	0.53	0.17*	0.08	336
Spoke w VE in past week	0.43	0.40	0.63	0.23**	0.08	336
Shared meal w VE in past week	0.07	0.08	0.05	-0.03	0.04	336
Worships at same church as VE	0.04	0.03	0.05	0.02	0.03	310
VE connections index (village standardized)	0.05	0.00	0.38	0.38*	0.17	310
VE connections index (excl. church, village standardized)	0.04	0.00	0.35	0.36*	0.16	336

Note: Two sample t-test with pooled variance. *p<0.05; **p<0.01; ***p<0.001

Table A12: Difference-in-means (Non-duplicates only)

	Survey mean	No beacon detected	Beacon detected	Difference	Std. Error	Total n
Match						
Child between 5 and 12	0.52	0.51	0.56	0.05	0.06	375
Retired adult	0.32	0.29	0.40	0.11	0.06	375
Only retired adults	0.06	0.05	0.09	0.04	0.03	375
Household size	4.15	4.18	4.03	-0.15	0.27	375
Already owns lantern	0.25	0.25	0.22	-0.03	0.05	375
Connected to electric grid	0.18	0.20	0.11	-0.09	0.05	375
Owns solar home system	0.70	0.71	0.68	-0.03	0.06	375
Assets index (village standardized)	-0.01	0.01	-0.08	-0.08	0.12	375
Housing quality index (village standardized)	0.07	0.01	0.27	0.26	0.14	358
Lived poverty index (village standardized)	0.06	-0.01	0.26	0.26*	0.12	369
VE is immediate family member	0.24	0.24	0.28	0.04	0.05	364
VE is extended family member	0.33	0.31	0.38	0.07	0.06	364
VE is related	0.38	0.36	0.46	0.09	0.06	364
Spoke w VE in past week	0.43	0.39	0.56	0.16**	0.06	364
Shared meal w VE in past week	0.07	0.07	0.08	0.00	0.03	364
Worships at same church as VE	0.04	0.03	0.04	0.01	0.02	336
VE connections index (village standardized)	0.04	0.00	0.18	0.18	0.13	336
VE connections index (excl. church, village standardized)	0.04	0.00	0.17	0.18	0.13	364
Verified Match						
Child between 5 and 12	0.54	0.51	0.68	0.18*	0.07	342
Retired adult	0.31	0.29	0.39	0.09	0.07	342
Only retired adults	0.05	0.05	0.09	0.04	0.03	342
Household size	4.23	4.18	4.49	0.31	0.33	342
Already owns lantern	0.27	0.25	0.35	0.10	0.06	342
Connected to electric grid	0.18	0.20	0.11	-0.09	0.06	342
Owns solar home system	0.70	0.71	0.67	-0.04	0.07	342
Assets index (village standardized)	0.01	0.01	0.03	0.02	0.14	342
Housing quality index (village standardized)	0.05	0.01	0.27	0.26	0.16	328
Lived poverty index (village standardized)	0.06	-0.01	0.37	0.38*	0.15	336
VE is immediate family member	0.25	0.24	0.34	0.11	0.07	332
VE is extended family member	0.33	0.31	0.45	0.13	0.07	332
VE is related	0.39	0.36	0.53	0.17*	0.08	332
Spoke w VE in past week	0.42	0.39	0.62	0.22**	0.08	332
Shared meal w VE in past week	0.07	0.07	0.04	-0.03	0.04	332
Worships at same church as VE	0.04	0.03	0.05	0.01	0.03	306
VE connections index (village standardized)	0.05	0.00	0.37	0.37*	0.16	306
VE connections index (excl. church, village standardized)	0.05	0.00	0.34	0.35*	0.16	332
Confident Match						
Child between 5 and 12	0.52	0.51	0.60	0.09	0.08	335
Retired adult	0.31	0.29	0.38	0.09	0.07	335
Only retired adults	0.06	0.05	0.14	0.09**	0.04	335
Household size	4.16	4.18	4.04	-0.14	0.35	335
Already owns lantern	0.25	0.25	0.24	-0.01	0.07	335
Connected to electric grid	0.19	0.20	0.10	-0.10	0.06	335
Owns solar home system	0.70	0.71	0.68	-0.03	0.07	335
Assets index (village standardized)	0.00	0.01	-0.04	-0.05	0.15	335
Housing quality index (village standardized)	0.02	0.01	0.06	0.05	0.15	322
Lived poverty index (village standardized)	0.02	-0.01	0.16	0.17	0.15	329
VE is immediate family member	0.26	0.24	0.41	0.18*	0.07	326
VE is extended family member	0.33	0.31	0.46	0.15	0.08	326
VE is related	0.39	0.36	0.54	0.17*	0.08	326
Spoke w VE in past week	0.42	0.39	0.63	0.24**	0.08	326
Shared meal w VE in past week	0.07	0.07	0.05	-0.02	0.04	326
Worships at same church as VE	0.04	0.03	0.05	0.02	0.03	300
VE connections index (village standardized)	0.05	0.00	0.38	0.38*	0.17	300
VE connections index (excl. church, village standardized)	0.04	0.00	0.36	0.36*	0.17	326

Note: Two sample t-test with pooled variance. *p<0.05; **p<0.01; ***p<0.001

Table A13: Difference-in-means (Most restrictive)

	Survey mean	No beacon detected	Beacon detected	Difference	Std. Error	Total n
Match						
Child between 5 and 12	0.54	0.52	0.59	0.07	0.07	224
Retired adult	0.33	0.28	0.45	0.17*	0.07	224
Only retired adults	0.06	0.04	0.11	0.07	0.04	224
Household size	4.19	4.18	4.20	0.02	0.33	224
Already owns lantern	0.26	0.27	0.23	-0.03	0.07	224
Connected to electric grid	0.15	0.16	0.11	-0.05	0.05	224
Owns solar home system	0.71	0.72	0.70	-0.02	0.07	224
Assets index (village standardized)	-0.07	-0.09	-0.03	0.06	0.13	224
Housing quality index (village standardized)	0.01	-0.03	0.11	0.14	0.16	219
Lived poverty index (village standardized)	0.10	0.00	0.34	0.35*	0.14	219
VE is immediate family member	0.26	0.25	0.29	0.04	0.07	215
VE is extended family member	0.35	0.34	0.38	0.04	0.08	215
VE is related	0.41	0.39	0.47	0.09	0.08	215
Spoke w VE in past week	0.46	0.41	0.60	0.19*	0.08	215
Shared meal w VE in past week	0.07	0.08	0.07	0.00	0.04	215
Worships at same church as VE	0.03	0.03	0.02	-0.01	0.03	202
VE connections index (village standardized)	0.11	0.07	0.21	0.15	0.17	202
VE connections index (excl. church, village standardized)	0.10	0.06	0.21	0.14	0.16	215
Verified Match						
Child between 5 and 12	0.56	0.52	0.67	0.15	0.08	209
Retired adult	0.31	0.28	0.41	0.13	0.08	209
Only retired adults	0.06	0.04	0.10	0.06	0.04	209
Household size	4.23	4.18	4.39	0.21	0.36	209
Already owns lantern	0.28	0.27	0.31	0.04	0.07	209
Connected to electric grid	0.14	0.16	0.08	-0.08	0.06	209
Owns solar home system	0.71	0.72	0.67	-0.05	0.07	209
Assets index (village standardized)	-0.07	-0.09	-0.01	0.08	0.14	209
Housing quality index (village standardized)	0.02	-0.03	0.19	0.22	0.18	204
Lived poverty index (village standardized)	0.08	0.00	0.36	0.37*	0.16	204
VE is immediate family member	0.27	0.25	0.32	0.08	0.08	200
VE is extended family member	0.36	0.34	0.42	0.08	0.09	200
VE is related	0.41	0.39	0.50	0.11	0.09	200
Spoke w VE in past week	0.45	0.41	0.62	0.21*	0.09	200
Shared meal w VE in past week	0.07	0.08	0.05	-0.03	0.05	200
Worships at same church as VE	0.03	0.03	0.03	-0.01	0.03	187
VE connections index (village standardized)	0.12	0.07	0.33	0.27	0.19	187
VE connections index (excl. church, village standardized)	0.11	0.06	0.32	0.26	0.18	200
Confident Match						
Child between 5 and 12	0.54	0.52	0.62	0.09	0.09	199
Retired adult	0.30	0.28	0.38	0.10	0.08	199
Only retired adults	0.07	0.04	0.15	0.11*	0.04	199
Household size	4.15	4.18	4.00	-0.18	0.40	199
Already owns lantern	0.26	0.27	0.23	-0.04	0.08	199
Connected to electric grid	0.15	0.16	0.08	-0.09	0.06	199
Owns solar home system	0.71	0.72	0.69	-0.03	0.08	199
Assets index (village standardized)	-0.09	-0.09	-0.07	0.02	0.16	199
Housing quality index (village standardized)	-0.05	-0.03	-0.14	-0.11	0.15	195
Lived poverty index (village standardized)	0.05	0.00	0.28	0.28	0.17	194
VE is immediate family member	0.28	0.25	0.41	0.16	0.09	192
VE is extended family member	0.36	0.34	0.44	0.09	0.09	192
VE is related	0.41	0.39	0.50	0.11	0.10	192
Spoke w VE in past week	0.46	0.41	0.69	0.27**	0.09	192
Shared meal w VE in past week	0.07	0.08	0.06	-0.01	0.05	192
Worships at same church as VE	0.03	0.03	0.03	0.00	0.04	180
VE connections index (village standardized)	0.11	0.07	0.33	0.27	0.21	180
VE connections index (excl. church, village standardized)	0.11	0.06	0.35	0.29	0.20	192

Note: Two sample t-test with pooled variance. *p<0.05; **p<0.01; ***p<0.001

J.2 Eligible non-recipient versus eligible recipient households

J.2.1 Alternative Match Criteria

Table A14: Difference-in-means (Confident Matches)

	Survey mean	No beacon detected	Beacon detected	Difference	Std./nError	Total n households
Child under 5 (binary)	1.00	1.00	1.00	0.00	NA	191
Children under 5 (count)	1.27	1.28	1.27	-0.01	0.08	191
Child between 5 and 12	0.68	0.58	0.76	0.18**	0.07	191
Retired adult	0.14	0.16	0.13	-0.03	0.05	191
Only retired adults	0.00	0.00	0.00	0.00	NA	191
Household size	5.43	5.17	5.67	0.51	0.30	191
Already owns lantern	0.21	0.24	0.19	-0.06	0.06	191
Connected to electric grid	0.12	0.17	0.07	-0.10*	0.05	191
Owns solar home system	0.69	0.68	0.70	0.03	0.07	191
Assets index (village standardized)	-0.11	-0.01	-0.20	-0.18	0.13	191
Housing quality index (village standardized)	-0.34	-0.20	-0.47	-0.27**	0.10	184
Lived poverty index (village standardized)	0.17	-0.06	0.38	0.45**	0.16	190
VE is immediate family member	0.19	0.16	0.23	0.07	0.06	186
VE is extended family member	0.26	0.22	0.30	0.08	0.06	186
VE is related	0.33	0.28	0.39	0.11	0.07	186
Spoke w VE in past week	0.45	0.32	0.56	0.24***	0.07	186
Shared meal w VE in past week	0.09	0.07	0.10	0.04	0.04	186
Worships at same church as VE	0.04	0.04	0.04	0.01	0.03	170
VE connections index (village standardized)	-0.07	-0.19	0.03	0.22	0.15	175
VE connections index (excl. church, village standardized)	-0.07	-0.20	0.04	0.24	0.14	191

Note: Two sample t-test with pooled variance. *p<0.05; **p<0.01; ***p<0.001

Table A15: Difference-in-means (Verified Matches)

	Survey mean	No beacon detected	Beacon detected	Difference	Std./nError	Total n households
Child under 5 (binary)	1.00	1.00	1.00	0.00	NA	222
Children under 5 (count)	1.27	1.28	1.27	-0.01	0.07	222
Child between 5 and 12	0.70	0.58	0.79	0.21***	0.06	222
Retired adult	0.14	0.16	0.14	-0.02	0.05	222
Only retired adults	0.00	0.00	0.00	0.00	NA	222
Household size	5.60	5.17	5.89	0.73*	0.28	222
Already owns lantern	0.23	0.24	0.22	-0.02	0.06	222
Connected to electric grid	0.14	0.17	0.11	-0.05	0.05	222
Owns solar home system	0.68	0.68	0.68	0.00	0.06	222
Assets index (village standardized)	-0.10	-0.01	-0.15	-0.14	0.13	222
Housing quality index (village standardized)	-0.32	-0.20	-0.40	-0.20	0.11	212
Lived poverty index (village standardized)	0.26	-0.06	0.48	0.54***	0.15	221
VE is immediate family member	0.18	0.16	0.20	0.04	0.05	216
VE is extended family member	0.27	0.22	0.30	0.08	0.06	216
VE is related	0.33	0.28	0.37	0.10	0.07	216
Spoke w VE in past week	0.47	0.32	0.57	0.25***	0.07	216
Shared meal w VE in past week	0.09	0.07	0.10	0.04	0.04	216
Worships at same church as VE	0.05	0.04	0.05	0.01	0.03	195
VE connections index (village standardized)	-0.04	-0.19	0.06	0.25	0.14	201
VE connections index (excl. church, village standardized)	-0.06	-0.20	0.03	0.23	0.13	222

Note: Two sample t-test with pooled variance. *p<0.05; **p<0.01; ***p<0.001

J.2.2 Alternative Data Quality Controls

Table A16: Difference-in-means (Most proximate household to survey site is interviewed household)

	Survey mean	No beacon detected	Beacon detected	Difference	Std./nError	Total n
Match						
Children under 5 (count)	1.27	1.31	1.25	-0.06	0.10	161
Child between 5 and 12	0.71	0.62	0.75	0.13	0.08	161
Retired adult	0.11	0.07	0.13	0.05	0.06	161
Household size	5.58	5.24	5.71	0.47	0.37	161
Already owns lantern	0.19	0.26	0.16	-0.10	0.07	161
Connected to electric grid	0.12	0.17	0.10	-0.07	0.06	161
Owns solar home system	0.70	0.67	0.71	0.05	0.08	161
Assets index (village standardized)	-0.17	-0.09	-0.20	-0.11	0.16	161
Housing quality index (village standardized)	-0.35	-0.22	-0.40	-0.18	0.13	157
Lived poverty index (village standardized)	0.32	-0.30	0.54	0.84***	0.20	161
VE is immediate family member	0.19	0.14	0.21	0.07	0.07	156
VE is extended family member	0.27	0.21	0.29	0.08	0.08	156
VE is related	0.33	0.26	0.35	0.09	0.08	156
Spoke w VE in past week	0.50	0.31	0.57	0.26**	0.09	156
Shared meal w VE in past week	0.08	0.05	0.10	0.05	0.05	156
Worships at same church as VE	0.06	0.05	0.06	0.00	0.04	145
VE connections index (village standardized)	-0.01	-0.14	0.03	0.18	0.19	150
VE connections index (excl. church, village standardized)	-0.05	-0.20	0.01	0.21	0.18	161
Verified Match						
Children under 5 (count)	1.27	1.31	1.25	-0.06	0.10	145
Child between 5 and 12	0.74	0.62	0.79	0.17*	0.08	145
Retired adult	0.12	0.07	0.14	0.06	0.06	145
Household size	5.65	5.24	5.82	0.58	0.38	145
Already owns lantern	0.21	0.26	0.18	-0.08	0.07	145
Connected to electric grid	0.12	0.17	0.10	-0.07	0.06	145
Owns solar home system	0.68	0.67	0.68	0.01	0.09	145
Assets index (village standardized)	-0.15	-0.09	-0.17	-0.08	0.16	145
Housing quality index (village standardized)	-0.36	-0.22	-0.42	-0.20	0.12	143
Lived poverty index (village standardized)	0.29	-0.30	0.54	0.84***	0.20	145
VE is immediate family member	0.18	0.14	0.20	0.06	0.07	141
VE is extended family member	0.27	0.21	0.29	0.08	0.08	141
VE is related	0.33	0.26	0.36	0.10	0.09	141
Spoke w VE in past week	0.50	0.31	0.58	0.27**	0.09	141
Shared meal w VE in past week	0.08	0.05	0.09	0.04	0.05	141
Worships at same church as VE	0.05	0.05	0.05	0.00	0.04	132
VE connections index (village standardized)	0.02	-0.14	0.08	0.22	0.20	136
VE connections index (excl. church, village standardized)	-0.03	-0.20	0.04	0.24	0.19	145
Confident Match						
Children under 5 (count)	1.28	1.31	1.26	-0.05	0.11	130
Child between 5 and 12	0.71	0.62	0.75	0.13	0.09	130
Retired adult	0.12	0.07	0.15	0.08	0.06	130
Household size	5.53	5.24	5.67	0.43	0.39	130
Already owns lantern	0.20	0.26	0.17	-0.09	0.08	130
Connected to electric grid	0.11	0.17	0.08	-0.09	0.06	130
Owns solar home system	0.69	0.67	0.70	0.04	0.09	130
Assets index (village standardized)	-0.19	-0.09	-0.24	-0.15	0.15	130
Housing quality index (village standardized)	-0.37	-0.22	-0.45	-0.23	0.12	127
Lived poverty index (village standardized)	0.17	-0.30	0.40	0.70***	0.20	130
VE is immediate family member	0.20	0.14	0.23	0.08	0.08	126
VE is extended family member	0.27	0.21	0.30	0.08	0.08	126
VE is related	0.33	0.26	0.37	0.11	0.09	126
Spoke w VE in past week	0.48	0.31	0.57	0.26**	0.09	126
Shared meal w VE in past week	0.08	0.05	0.10	0.05	0.05	126
Worships at same church as VE	0.04	0.05	0.04	-0.02	0.04	120
VE connections index (village standardized)	-0.03	-0.14	0.02	0.16	0.20	124
VE connections index (excl. church, village standardized)	-0.05	-0.20	0.02	0.22	0.19	130

Note: Two sample t-test with pooled variance. *p<0.05; **p<0.01; ***p<0.001

Table A17: Difference-in-means (Survey occurred within 1km of household locaiton)

	Survey mean	No beacon detected	Beacon detected	Difference	Std./nError	Total n
Match						
Children under 5 (count)	1.27	1.28	1.27	-0.01	0.07	242
Child between 5 and 12	0.68	0.58	0.74	0.15*	0.06	242
Retired adult	0.13	0.15	0.12	-0.02	0.05	242
Household size	5.57	5.20	5.78	0.58*	0.28	242
Already owns lantern	0.21	0.24	0.19	-0.05	0.05	242
Connected to electric grid	0.14	0.17	0.12	-0.05	0.05	242
Owns solar home system	0.70	0.69	0.71	0.03	0.06	242
Assets index (village standardized)	-0.10	-0.01	-0.16	-0.16	0.12	242
Housing quality index (village standardized)	-0.30	-0.18	-0.36	-0.18	0.11	229
Lived poverty index (village standardized)	0.27	-0.06	0.47	0.53***	0.15	241
VE is immediate family member	0.19	0.16	0.21	0.05	0.05	235
VE is extended family member	0.27	0.22	0.29	0.07	0.06	235
VE is related	0.33	0.27	0.36	0.09	0.06	235
Spoke w VE in past week	0.47	0.31	0.56	0.25***	0.07	235
Shared meal w VE in past week	0.09	0.07	0.10	0.04	0.04	235
Worships at same church as VE	0.05	0.04	0.06	0.02	0.03	213
VE connections index (village standardized)	-0.06	-0.19	0.02	0.21	0.14	220
VE connections index (excl. church, village standardized)	-0.08	-0.21	0.00	0.21	0.13	242
Verified Match						
Children under 5 (count)	1.27	1.28	1.27	-0.02	0.07	221
Child between 5 and 12	0.71	0.58	0.79	0.20**	0.06	221
Retired adult	0.14	0.15	0.14	-0.01	0.05	221
Household size	5.62	5.20	5.89	0.69*	0.28	221
Already owns lantern	0.23	0.24	0.22	-0.02	0.06	221
Connected to electric grid	0.14	0.17	0.11	-0.05	0.05	221
Owns solar home system	0.68	0.69	0.68	0.00	0.06	221
Assets index (village standardized)	-0.09	-0.01	-0.15	-0.15	0.13	221
Housing quality index (village standardized)	-0.31	-0.18	-0.40	-0.21	0.11	211
Lived poverty index (village standardized)	0.26	-0.06	0.48	0.54***	0.15	220
VE is immediate family member	0.18	0.16	0.20	0.04	0.05	215
VE is extended family member	0.27	0.22	0.30	0.08	0.06	215
VE is related	0.33	0.27	0.37	0.10	0.07	215
Spoke w VE in past week	0.47	0.31	0.57	0.26***	0.07	215
Shared meal w VE in past week	0.09	0.07	0.10	0.04	0.04	215
Worships at same church as VE	0.05	0.04	0.05	0.01	0.03	195
VE connections index (village standardized)	-0.04	-0.19	0.06	0.25	0.14	201
VE connections index (excl. church, village standardized)	-0.07	-0.21	0.03	0.24	0.13	221
Confident Match						
Children under 5 (count)	1.27	1.28	1.27	-0.01	0.08	190
Child between 5 and 12	0.68	0.58	0.76	0.18**	0.07	190
Retired adult	0.14	0.15	0.13	-0.02	0.05	190
Household size	5.45	5.20	5.67	0.47	0.30	190
Already owns lantern	0.21	0.24	0.19	-0.05	0.06	190
Connected to electric grid	0.12	0.17	0.07	-0.10*	0.05	190
Owns solar home system	0.69	0.69	0.70	0.02	0.07	190
Assets index (village standardized)	-0.11	-0.01	-0.20	-0.19	0.13	190
Housing quality index (village standardized)	-0.34	-0.18	-0.47	-0.29**	0.10	183
Lived poverty index (village standardized)	0.18	-0.06	0.38	0.44**	0.16	189
VE is immediate family member	0.19	0.16	0.23	0.07	0.06	185
VE is extended family member	0.26	0.22	0.30	0.08	0.07	185
VE is related	0.33	0.27	0.39	0.12	0.07	185
Spoke w VE in past week	0.44	0.31	0.56	0.25***	0.07	185
Shared meal w VE in past week	0.09	0.07	0.10	0.04	0.04	185
Worships at same church as VE	0.04	0.04	0.04	0.01	0.03	170
VE connections index (village standardized)	-0.07	-0.19	0.03	0.22	0.15	175
VE connections index (excl. church, village standardized)	-0.08	-0.21	0.04	0.25	0.14	190

Note: Two sample t-test with pooled variance. $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.010$

Table A18: Difference-in-means (Non-duplicates only)

	Survey mean	No beacon detected	Beacon detected	Difference	Std./nError	Total n
Match						
Children under 5 (count)	1.26	1.27	1.26	-0.01	0.07	236
Child between 5 and 12	0.67	0.57	0.73	0.16*	0.06	236
Retired adult	0.14	0.16	0.13	-0.03	0.05	236
Household size	5.55	5.17	5.78	0.61*	0.28	236
Already owns lantern	0.20	0.24	0.18	-0.05	0.05	236
Connected to electric grid	0.14	0.17	0.12	-0.05	0.05	236
Owns solar home system	0.70	0.67	0.71	0.04	0.06	236
Assets index (village standardized)	-0.10	-0.02	-0.15	-0.13	0.12	236
Housing quality index (village standardized)	-0.30	-0.19	-0.37	-0.18	0.11	225
Lived poverty index (village standardized)	0.27	-0.06	0.47	0.53***	0.15	235
VE is immediate family member	0.19	0.16	0.21	0.05	0.05	229
VE is extended family member	0.27	0.22	0.30	0.08	0.06	229
VE is related	0.34	0.28	0.37	0.09	0.06	229
Spoke w VE in past week	0.47	0.33	0.56	0.24***	0.07	229
Shared meal w VE in past week	0.09	0.07	0.11	0.04	0.04	229
Worships at same church as VE	0.05	0.04	0.06	0.02	0.03	207
VE connections index (village standardized)	-0.06	-0.19	0.02	0.21	0.14	214
VE connections index (excl. church, village standardized)	-0.07	-0.20	0.00	0.20	0.13	236
Verified Match						
Children under 5 (count)	1.26	1.27	1.26	-0.01	0.07	217
Child between 5 and 12	0.70	0.57	0.78	0.21***	0.06	217
Retired adult	0.15	0.16	0.14	-0.02	0.05	217
Household size	5.59	5.17	5.88	0.71*	0.29	217
Already owns lantern	0.22	0.24	0.21	-0.03	0.06	217
Connected to electric grid	0.14	0.17	0.12	-0.05	0.05	217
Owns solar home system	0.68	0.67	0.69	0.01	0.06	217
Assets index (village standardized)	-0.09	-0.02	-0.14	-0.12	0.13	217
Housing quality index (village standardized)	-0.31	-0.19	-0.39	-0.20	0.12	208
Lived poverty index (village standardized)	0.27	-0.06	0.49	0.55***	0.15	216
VE is immediate family member	0.18	0.16	0.20	0.04	0.05	211
VE is extended family member	0.27	0.22	0.30	0.08	0.06	211
VE is related	0.34	0.28	0.38	0.10	0.07	211
Spoke w VE in past week	0.46	0.33	0.57	0.24***	0.07	211
Shared meal w VE in past week	0.09	0.07	0.11	0.04	0.04	211
Worships at same church as VE	0.05	0.04	0.05	0.01	0.03	191
VE connections index (village standardized)	-0.04	-0.19	0.05	0.24	0.14	197
VE connections index (excl. church, village standardized)	-0.07	-0.20	0.02	0.22	0.14	217
Confident Match						
Children under 5 (count)	1.26	1.27	1.25	-0.02	0.08	186
Child between 5 and 12	0.67	0.57	0.76	0.19**	0.07	186
Retired adult	0.15	0.16	0.13	-0.02	0.05	186
Household size	5.44	5.17	5.68	0.51	0.30	186
Already owns lantern	0.21	0.24	0.19	-0.05	0.06	186
Connected to electric grid	0.12	0.17	0.07	-0.10*	0.05	186
Owns solar home system	0.69	0.67	0.71	0.04	0.07	186
Assets index (village standardized)	-0.11	-0.02	-0.19	-0.17	0.13	186
Housing quality index (village standardized)	-0.33	-0.19	-0.46	-0.27*	0.11	180
Lived poverty index (village standardized)	0.18	-0.06	0.40	0.46**	0.16	185
VE is immediate family member	0.19	0.16	0.23	0.07	0.06	181
VE is extended family member	0.27	0.22	0.30	0.08	0.07	181
VE is related	0.34	0.28	0.39	0.11	0.07	181
Spoke w VE in past week	0.45	0.33	0.57	0.24**	0.07	181
Shared meal w VE in past week	0.09	0.07	0.11	0.04	0.04	181
Worships at same church as VE	0.04	0.04	0.05	0.01	0.03	166
VE connections index (village standardized)	-0.08	-0.19	0.02	0.21	0.15	171
VE connections index (excl. church, village standardized)	-0.08	-0.20	0.03	0.23	0.14	186

Note: Two sample t-test with pooled variance. $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Table A19: Difference-in-means (Most restrictive)

	Survey mean	No beacon detected	Beacon detected	Difference	Std./nError	Total n
Match						
Children under 5 (count)	1.25	1.29	1.24	-0.06	0.10	155
Child between 5 and 12	0.71	0.61	0.75	0.14	0.08	155
Retired adult	0.12	0.07	0.13	0.06	0.06	155
Household size	5.57	5.24	5.69	0.45	0.38	155
Already owns lantern	0.18	0.24	0.16	-0.09	0.07	155
Connected to electric grid	0.12	0.17	0.11	-0.07	0.06	155
Owns solar home system	0.70	0.66	0.72	0.06	0.08	155
Assets index (village standardized)	-0.17	-0.10	-0.20	-0.10	0.16	155
Housing quality index (village standardized)	-0.35	-0.20	-0.40	-0.20	0.13	152
Lived poverty index (village standardized)	0.32	-0.29	0.54	0.83***	0.20	155
VE is immediate family member	0.19	0.15	0.21	0.06	0.07	150
VE is extended family member	0.27	0.22	0.29	0.07	0.08	150
VE is related	0.33	0.27	0.36	0.09	0.09	150
Spoke w VE in past week	0.51	0.32	0.58	0.26**	0.09	150
Shared meal w VE in past week	0.09	0.05	0.10	0.05	0.05	150
Worships at same church as VE	0.06	0.05	0.06	0.01	0.04	140
VE connections index (village standardized)	-0.01	-0.14	0.03	0.18	0.19	145
VE connections index (excl. church, village standardized)	-0.04	-0.19	0.01	0.19	0.18	155
Verified Match						
Children under 5 (count)	1.26	1.29	1.24	-0.05	0.10	141
Child between 5 and 12	0.73	0.61	0.78	0.17*	0.08	141
Retired adult	0.12	0.07	0.14	0.07	0.06	141
Household size	5.64	5.24	5.80	0.56	0.39	141
Already owns lantern	0.20	0.24	0.18	-0.06	0.07	141
Connected to electric grid	0.12	0.17	0.10	-0.07	0.06	141
Owns solar home system	0.68	0.66	0.69	0.03	0.09	141
Assets index (village standardized)	-0.15	-0.10	-0.17	-0.07	0.16	141
Housing quality index (village standardized)	-0.35	-0.20	-0.41	-0.21	0.12	139
Lived poverty index (village standardized)	0.30	-0.29	0.55	0.84***	0.20	141
VE is immediate family member	0.18	0.15	0.20	0.05	0.07	137
VE is extended family member	0.27	0.22	0.29	0.07	0.08	137
VE is related	0.34	0.27	0.36	0.10	0.09	137
Spoke w VE in past week	0.50	0.32	0.57	0.26**	0.09	137
Shared meal w VE in past week	0.08	0.05	0.09	0.04	0.05	137
Worships at same church as VE	0.05	0.05	0.05	0.00	0.04	129
VE connections index (village standardized)	0.01	-0.14	0.07	0.21	0.20	133
VE connections index (excl. church, village standardized)	-0.04	-0.19	0.03	0.21	0.19	141
Confident Match						
Children under 5 (count)	1.26	1.29	1.24	-0.05	0.11	125
Child between 5 and 12	0.70	0.61	0.75	0.14	0.09	125
Retired adult	0.13	0.07	0.15	0.08	0.06	125
Household size	5.54	5.24	5.68	0.43	0.40	125
Already owns lantern	0.19	0.24	0.17	-0.08	0.08	125
Connected to electric grid	0.11	0.17	0.08	-0.09	0.06	125
Owns solar home system	0.70	0.66	0.71	0.06	0.09	125
Assets index (village standardized)	-0.19	-0.10	-0.23	-0.13	0.15	125
Housing quality index (village standardized)	-0.36	-0.20	-0.43	-0.23	0.12	123
Lived poverty index (village standardized)	0.19	-0.29	0.42	0.71***	0.21	125
VE is immediate family member	0.20	0.15	0.22	0.08	0.08	121
VE is extended family member	0.27	0.22	0.30	0.08	0.09	121
VE is related	0.34	0.27	0.38	0.11	0.09	121
Spoke w VE in past week	0.49	0.32	0.58	0.26**	0.09	121
Shared meal w VE in past week	0.08	0.05	0.10	0.05	0.05	121
Worships at same church as VE	0.04	0.05	0.04	-0.01	0.04	116
VE connections index (village standardized)	-0.04	-0.14	0.01	0.15	0.20	120
VE connections index (excl. church, village standardized)	-0.05	-0.19	0.01	0.20	0.19	125

Note: Two sample t-test with pooled variance. *p<0.05; **p<0.01; ***p<0.001

J.3 Difference-in-means: R1 matches versus R5 matches

Table A20: Most proximate household to survey site is interviewed household

	R1 Match mean	R1 Match households	R5 Match mean	R5 Match households	Difference	Std. error
Child under 5 (binary)	0.58	38	0.58	31	0.00	0.12
Children under 5 (count)	0.68	38	0.74	31	-0.06	0.17
Child between 5 and 12	0.63	38	0.74	31	-0.11	0.11
Retired adult	0.32	38	0.19	31	0.12	0.11
Only retired adults	0.03	38	0.03	31	-0.01	0.04
Household size	5.18	38	5.32	31	-0.14	0.50
Already owns lantern	0.26	38	0.16	31	0.10	0.10
Connected to electric grid	0.11	38	0.10	31	0.01	0.07
Owns solar home system	0.66	38	0.61	31	0.04	0.12
Assets index (village standardized)	0.11	38	0.07	31	0.05	0.23
Housing quality index (village standardized)	0.27	38	-0.48	31	0.75*	0.29
Lived poverty index (village standardized)	0.32	38	0.72	31	-0.39	0.27
VE is immediate family member	0.29	34	0.10	30	0.19	0.10
VE is extended family member	0.32	34	0.17	30	0.16	0.11
VE is related	0.44	34	0.20	30	0.24*	0.12
Spoke w VE in past week	0.65	34	0.50	30	0.15	0.12
Shared meal w VE in past week	0.15	34	0.03	30	0.11	0.07
Worships at same church as VE	0.03	32	0.07	28	-0.04	0.06
VE connections index (village standardized)	0.10	36	-0.41	29	0.51*	0.23
VE connections index (excl. church, village standardized)	0.05	38	-0.38	31	0.43	0.22

Note: Two sample t-test with pooled variance. *p<0.05; **p<0.01; ***p<0.001

Table A21: Survey occurred within 1km of household location

	R1 Match mean	R1 Match households	R5 Match mean	R5 Match households	Difference	Std. error
Child under 5 (binary)	0.63	52	0.53	49	0.10	0.10
Children under 5 (count)	0.77	52	0.65	49	0.12	0.14
Child between 5 and 12	0.60	52	0.67	49	-0.08	0.10
Retired adult	0.23	52	0.18	49	0.05	0.08
Only retired adults	0.02	52	0.04	49	-0.02	0.03
Household size	5.10	52	4.86	49	0.24	0.41
Already owns lantern	0.23	52	0.24	49	-0.01	0.09
Connected to electric grid	0.13	52	0.08	49	0.05	0.06
Owns solar home system	0.67	52	0.63	49	0.04	0.10
Assets index (village standardized)	-0.04	52	0.03	49	-0.06	0.18
Housing quality index (village standardized)	0.16	50	-0.21	45	0.38	0.27
Lived poverty index (village standardized)	0.19	51	0.57	49	-0.37	0.22
VE is immediate family member	0.26	47	0.13	47	0.13	0.08
VE is extended family member	0.30	47	0.21	47	0.09	0.09
VE is related	0.40	47	0.28	47	0.13	0.10
Spoke w VE in past week	0.62	47	0.47	47	0.15	0.10
Shared meal w VE in past week	0.15	47	0.04	47	0.11	0.06
Worships at same church as VE	0.07	44	0.05	42	0.02	0.05
VE connections index (village standardized)	-0.01	49	-0.29	44	0.29	0.19
VE connections index (excl. church, village standardized)	-0.02	52	-0.24	49	0.22	0.19

Note: Two sample t-test with pooled variance. *p<0.05; **p<0.01; ***p<0.001

Table A22: Non-duplicates only

	R1 Match mean	R1 Match households	R5 Match mean	R5 Match households	Difference	Std. error
Child under 5 (binary)	0.66	47	0.53	47	0.13	0.10
Children under 5 (count)	0.79	47	0.64	47	0.15	0.14
Child between 5 and 12	0.57	47	0.66	47	-0.09	0.10
Retired adult	0.21	47	0.19	47	0.02	0.08
Only retired adults	0.02	47	0.04	47	-0.02	0.04
Household size	4.98	47	4.81	47	0.17	0.43
Already owns lantern	0.21	47	0.26	47	-0.04	0.09
Connected to electric grid	0.13	47	0.09	47	0.04	0.06
Owns solar home system	0.70	47	0.66	47	0.04	0.10
Assets index (village standardized)	-0.09	47	0.05	47	-0.14	0.19
Housing quality index (village standardized)	0.07	45	-0.19	43	0.26	0.24
Lived poverty index (village standardized)	0.14	46	0.54	47	-0.39	0.22
VE is immediate family member	0.21	43	0.13	45	0.08	0.08
VE is extended family member	0.26	43	0.22	45	0.03	0.09
VE is related	0.37	43	0.29	45	0.08	0.10
Spoke w VE in past week	0.60	43	0.47	45	0.14	0.11
Shared meal w VE in past week	0.16	43	0.04	45	0.12	0.06
Worships at same church as VE	0.08	40	0.05	40	0.03	0.05
VE connections index (village standardized)	-0.10	44	-0.27	42	0.18	0.20
VE connections index (excl. church, village standardized)	-0.11	47	-0.23	47	0.12	0.19

Note: Two sample t-test with pooled variance. *p<0.05; **p<0.01; ***p<0.001

Table A23: Most restrictive

	R1 Match mean	R1 Match households	R5 Match mean	R5 Match households	Difference	Std. error
Child under 5 (binary)	0.61	33	0.59	29	0.02	0.13
Children under 5 (count)	0.70	33	0.72	29	-0.03	0.18
Child between 5 and 12	0.61	33	0.72	29	-0.12	0.12
Retired adult	0.30	33	0.21	29	0.10	0.11
Only retired adults	0.03	33	0.03	29	0.00	0.05
Household size	5.03	33	5.28	29	-0.25	0.53
Already owns lantern	0.24	33	0.17	29	0.07	0.10
Connected to electric grid	0.09	33	0.10	29	-0.01	0.08
Owns solar home system	0.70	33	0.66	29	0.04	0.12
Assets index (village standardized)	0.07	33	0.11	29	-0.04	0.24
Housing quality index (village standardized)	0.16	33	-0.46	29	0.62**	0.22
Lived poverty index (village standardized)	0.27	33	0.68	29	-0.41	0.27
VE is immediate family member	0.23	30	0.11	28	0.13	0.10
VE is extended family member	0.27	30	0.18	28	0.09	0.11
VE is related	0.40	30	0.21	28	0.19	0.12
Spoke w VE in past week	0.63	30	0.50	28	0.13	0.13
Shared meal w VE in past week	0.17	30	0.04	28	0.13	0.08
Worships at same church as VE	0.04	28	0.08	26	-0.04	0.06
VE connections index (village standardized)	-0.01	31	-0.39	27	0.37	0.23
VE connections index (excl. church, village standardized)	-0.06	33	-0.36	29	0.30	0.22

Note: Two sample t-test with pooled variance. *p<0.05; **p<0.01; ***p<0.001

K Multiple Regression Models

This section contains regression models predicting lantern receipt. Section K.1 contains the preferred specification using standard data quality controls, weighting to reflect unequal probability of selection into the sample (see Appendix L), and ordinary least squares regression. In Section K.2 to Section K.5, we examine robustness to alternative data quality controls. Section K.6 shows results using the standard data quality controls without weights to correct for selection bias. Section K.7 shows the results using standard data quality controls, weighting, and logistic regression.

K.1 Preferred specification (weighted, standard data quality controls)

Table A24: Which households received lanterns?

	Dependent variable:		
	Match	Verified Match	Confident Match
	(1)	(2)	(3)
Child under 5 yrs	0.139***	0.159***	0.116***
	(0.044)	(0.037)	(0.035)
Child bw 5 and 12 yrs	0.023	0.077***	0.049**
	(0.017)	(0.019)	(0.020)
Retired adult	−0.002	0.005	−0.013
	(0.020)	(0.020)	(0.019)
Already owns lantern	−0.044	0.010	−0.016
	(0.031)	(0.031)	(0.022)
Connected to electric grid	−0.068**	−0.036	−0.046*
	(0.029)	(0.029)	(0.025)
Owns solar home system	−0.053	−0.050	−0.029
	(0.040)	(0.040)	(0.029)
Asset index	−0.008	−0.004	−0.014*
	(0.017)	(0.015)	(0.009)
Housing quality index	0.007	−0.009	−0.010
	(0.024)	(0.015)	(0.011)
Lived poverty index	0.060***	0.053***	0.017
	(0.017)	(0.018)	(0.013)
VE is immediate family member	−0.045	−0.040	0.005
	(0.031)	(0.039)	(0.023)
Spoke w VE in past wk	0.100***	0.100***	0.075***
	(0.021)	(0.029)	(0.022)
Shared meal with VE in past wk	−0.056	−0.054	−0.037
	(0.042)	(0.036)	(0.026)
Constant	0.143***	0.042	0.041
	(0.051)	(0.049)	(0.036)
Observations	519	467	432
R^2	0.093	0.134	0.078
Adjusted R^2	0.071	0.111	0.052
Residual Std. Error	0.664 (df = 506)	0.600 (df = 454)	0.550 (df = 419)
F Statistic	4.304*** (df = 12; 506)	5.870*** (df = 12; 454)	2.959*** (df = 12; 419)

Note: Some measures dropped due to near multicollinearity. *p<0.05; **p<0.01; ***p<0.001

K.2 Most proximate household to survey site is interviewed household

Table A25: Regression Results

	Dependent variable:		
	Matched	Verified Match	Confident Match
	(1)	(2)	(3)
Child under 5 yrs	0.341***	0.374***	0.379***
	(0.042)	(0.044)	(0.046)
Child bw 5 and 12 yrs	0.051	0.098**	0.073
	(0.038)	(0.041)	(0.054)
Retired adult	0.087*	0.073	0.042
	(0.051)	(0.060)	(0.057)
Already owns lantern	−0.097	−0.035	−0.082*
	(0.059)	(0.051)	(0.046)
Connected to electric grid	−0.144***	−0.162***	−0.131**
	(0.048)	(0.056)	(0.060)
Owns solar home system	−0.096	−0.111	−0.095
	(0.066)	(0.077)	(0.060)
Asset index	−0.002	0.009	−0.012
	(0.037)	(0.037)	(0.039)
Housing quality index	−0.012	−0.021	−0.031
	(0.028)	(0.025)	(0.037)
Lived poverty index	0.085***	0.084***	0.061***
	(0.014)	(0.020)	(0.021)
VE is immediate family member	−0.040	−0.054	−0.0004
	(0.044)	(0.049)	(0.046)
Spoke w VE in past wk	0.104**	0.113*	0.124**
	(0.045)	(0.063)	(0.058)
Shared meal with VE in past wk	−0.029	−0.061	−0.069
	(0.042)	(0.056)	(0.043)
Constant	0.374***	0.284***	0.256***
	(0.062)	(0.068)	(0.079)
Observations	343	310	285
R^2	0.209	0.254	0.237
Adjusted R^2	0.180	0.224	0.204
Residual Std. Error	0.452 (df = 330)	0.441 (df = 297)	0.444 (df = 272)
F Statistic	7.264*** (df = 12; 330)	8.443*** (df = 12; 297)	7.058*** (df = 12; 272)

Note: See notes to Table A24 — *p<0.05; **p<0.01; ***p<0.001

K.3 Survey occurred within 1km of household location

Table A26: Regression Results

	Dependent variable:		
	Matched	Verified Match	Confident Match
	(1)	(2)	(3)
Child under 5 yrs	0.267***	0.310***	0.273***
	(0.059)	(0.059)	(0.063)
Child bw 5 and 12 yrs	0.070**	0.139***	0.108**
	(0.033)	(0.037)	(0.047)
Retired adult	0.006	0.017	−0.015
	(0.030)	(0.035)	(0.042)
Already owns lantern	−0.064	0.016	−0.049
	(0.056)	(0.051)	(0.047)
Connected to electric grid	−0.131***	−0.107**	−0.141**
	(0.044)	(0.048)	(0.060)
Owns solar home system	−0.050	−0.071	−0.067
	(0.064)	(0.069)	(0.058)
Asset index	−0.025	−0.008	−0.025
	(0.017)	(0.019)	(0.018)
Housing quality index	0.004	−0.020	−0.018
	(0.028)	(0.025)	(0.029)
Lived poverty index	0.069***	0.070***	0.038
	(0.020)	(0.024)	(0.024)
VE is immediate family member	−0.020	−0.025	0.026
	(0.047)	(0.058)	(0.051)
Spoke w VE in past wk	0.132***	0.141***	0.140***
	(0.029)	(0.045)	(0.041)
Shared meal with VE in past wk	−0.029	−0.066	−0.097**
	(0.052)	(0.050)	(0.043)
Constant	0.299***	0.161**	0.186**
	(0.076)	(0.075)	(0.074)
Observations	515	463	428
R^2	0.159	0.223	0.184
Adjusted R^2	0.139	0.203	0.160
Residual Std. Error	0.463 (df = 502)	0.437 (df = 450)	0.436 (df = 415)
F Statistic	7.896*** (df = 12; 502)	10.793*** (df = 12; 450)	7.787*** (df = 12; 415)

Note: See notes to Table A24 — *p<0.05; **p<0.01; ***p<0.001

K.4 Non-duplicates only

Table A27: Regression result

	Dependent variable:		
	Matched	Verified Match	Confident Match
	(1)	(2)	(3)
Child under 5 yrs	0.265***	0.305***	0.262***
	(0.061)	(0.059)	(0.062)
Child bw 5 and 12 yrs	0.066**	0.139***	0.097**
	(0.032)	(0.038)	(0.044)
Retired adult	0.002	0.001	−0.006
	(0.033)	(0.040)	(0.050)
Already owns lantern	−0.054	0.022	−0.035
	(0.064)	(0.058)	(0.052)
Connected to electric grid	−0.099*	−0.072	−0.120*
	(0.054)	(0.056)	(0.069)
Owns solar home system	−0.034	−0.054	−0.052
	(0.071)	(0.071)	(0.064)
Asset index	−0.026	−0.011	−0.021
	(0.018)	(0.021)	(0.020)
Housing quality index	0.00001	−0.015	−0.033
	(0.031)	(0.026)	(0.028)
Lived poverty index	0.066***	0.065***	0.044*
	(0.021)	(0.024)	(0.023)
VE is immediate family member	−0.039	−0.036	0.014
	(0.040)	(0.055)	(0.047)
Spoke w VE in past wk	0.139***	0.148***	0.136***
	(0.034)	(0.048)	(0.044)
Shared meal with VE in past wk	−0.044	−0.081	−0.084*
	(0.052)	(0.053)	(0.047)
Constant	0.283***	0.148*	0.177**
	(0.078)	(0.078)	(0.073)
Observations	497	450	416
R^2	0.151	0.209	0.172
Adjusted R^2	0.130	0.188	0.147
Residual Std. Error	0.465 (df = 484)	0.441 (df = 437)	0.440 (df = 403)
F Statistic	7.185*** (df = 12; 484)	9.647*** (df = 12; 437)	6.977*** (df = 12; 403)

Note: See notes to Table A24 — *p<0.05; **p<0.01; ***p<0.001

K.5 Most restrictive

Table A28: Regression Results

	Dependent variable:		
	Matched	Verified Match	Confident Match
	(1)	(2)	(3)
Child under 5 yrs	0.348***	0.374***	0.378***
	(0.045)	(0.045)	(0.042)
Child bw 5 and 12 yrs	0.048	0.096**	0.064
	(0.039)	(0.042)	(0.052)
Retired adult	0.094*	0.065	0.072
	(0.055)	(0.065)	(0.063)
Already owns lantern	−0.076	−0.023	−0.055
	(0.059)	(0.053)	(0.049)
Connected to electric grid	−0.137***	−0.147***	−0.126**
	(0.047)	(0.052)	(0.055)
Owns solar home system	−0.073	−0.089	−0.068
	(0.079)	(0.081)	(0.075)
Asset index	−0.0005	0.006	−0.003
	(0.039)	(0.039)	(0.041)
Housing quality index	−0.025	−0.017	−0.072***
	(0.035)	(0.027)	(0.026)
Lived poverty index	0.083***	0.078***	0.068***
	(0.015)	(0.020)	(0.019)
VE is immediate family member	−0.062	−0.059	−0.019
	(0.040)	(0.047)	(0.040)
Spoke w VE in past wk	0.116***	0.126**	0.125**
	(0.043)	(0.064)	(0.057)
Shared meal with VE in past wk	−0.046	−0.068	−0.057
	(0.038)	(0.058)	(0.045)
Constant	0.341***	0.263***	0.219***
	(0.065)	(0.071)	(0.078)
Observations	328	300	275
R^2	0.214	0.246	0.249
Adjusted R^2	0.184	0.215	0.215
Residual Std. Error	0.451 (df = 315)	0.444 (df = 287)	0.441 (df = 262)
F Statistic	7.148*** (df = 12; 315)	7.804*** (df = 12; 287)	7.247*** (df = 12; 262)

Note: See notes to Table A24 — *p<0.1; *p<0.05; **p<0.01; ***p<0.001

K.6 Unweighted Specification

Table A29: Main specifications, Unweighted

	Dependent variable:		
	Matched	Verified Match	Confident Match
	(1)	(2)	(3)
Child under 5 yrs	0.264***	0.306***	0.268***
	(0.059)	(0.060)	(0.064)
Child bw 5 and 12 yrs	0.068**	0.137***	0.106**
	(0.033)	(0.037)	(0.046)
Retired adult	−0.003	0.007	−0.025
	(0.032)	(0.037)	(0.044)
Already owns lantern	−0.067	0.013	−0.050
	(0.059)	(0.055)	(0.048)
Connected to electric grid	−0.119**	−0.093*	−0.126*
	(0.051)	(0.056)	(0.066)
Owns solar home system	−0.052	−0.073	−0.069
	(0.063)	(0.067)	(0.057)
Asset index	−0.024	−0.007	−0.024
	(0.017)	(0.019)	(0.018)
Housing quality index	0.006	−0.017	−0.014
	(0.027)	(0.024)	(0.028)
Lived poverty index	0.068***	0.069***	0.038
	(0.020)	(0.024)	(0.024)
VE is immediate family member	−0.022	−0.027	0.024
	(0.046)	(0.056)	(0.049)
Spoke w VE in past wk	0.129***	0.137***	0.135***
	(0.029)	(0.045)	(0.040)
Shared meal with VE in past wk	−0.025	−0.061	−0.092**
	(0.053)	(0.052)	(0.044)
Constant	0.305***	0.168**	0.194***
	(0.075)	(0.073)	(0.074)
Observations	519	467	432
R^2	0.154	0.215	0.175
Adjusted R^2	0.133	0.194	0.151
Residual Std. Error	0.464 (df = 506)	0.439 (df = 454)	0.438 (df = 419)
F Statistic	7.646*** (df = 12; 506)	10.372*** (df = 12; 454)	7.404*** (df = 12; 419)

Note: See notes to Table A24 — *p<0.05; **p<0.01; ***p<0.001

K.7 Logistic Regression

Table A30: Main specifications, Logistic regression

	Dependent variable:		
	Matched	Verified Match	Confident Match
	(1)	(2)	(3)
Child under 5 yrs	1.173***	1.464***	1.292***
	(0.282)	(0.317)	(0.332)
Child bw 5 and 12 yrs	0.315**	0.706***	0.554**
	(0.147)	(0.177)	(0.242)
Retired adult	−0.014	0.032	−0.152
	(0.148)	(0.213)	(0.249)
Already owns lantern	−0.314	0.088	−0.271
	(0.279)	(0.284)	(0.266)
Connected to electric grid	−0.604**	−0.567	−0.830*
	(0.265)	(0.363)	(0.463)
Owns solar home system	−0.244	−0.380	−0.378
	(0.294)	(0.354)	(0.297)
Asset index	−0.125	−0.052	−0.160
	(0.085)	(0.109)	(0.117)
Housing quality index	0.034	−0.093	−0.077
	(0.130)	(0.144)	(0.188)
Lived poverty index	0.324***	0.366***	0.201
	(0.103)	(0.132)	(0.125)
VE is immediate family member	−0.115	−0.155	0.122
	(0.221)	(0.308)	(0.281)
Spoke w VE in past wk	0.607***	0.717***	0.689***
	(0.147)	(0.239)	(0.223)
Shared meal with VE in past wk	−0.128	−0.324	−0.499**
	(0.253)	(0.286)	(0.243)
Constant	−0.865**	−1.645***	−1.476***
	(0.362)	(0.407)	(0.418)
Observations	519	467	432
Log Likelihood	−315.171	−258.409	−237.644
Akaike Inf. Crit.	656.343	542.817	501.288

Note: See notes to Table A24 — *p<0.05; **p<0.01; ***p<0.001

L Explanation for weighting decisions to correct for selection bias

L.1 Difference-in-means estimand

Where Y_i is receipt of a lantern and X_i is the status of a given covariate, the difference-in-means estimand can be defined as:

$$DIM = P(X_i = x|Y_i = 1) - P(X_i = x|Y_i = 0)$$

However, we do not observe data for all households. Let R_i represent whether the observation was recorded (i.e., whether the household was selected for inclusion in the survey). We can thus rewrite

$$P(X_i = x|Y_i = y) = P(X_i = x|Y_i = y, R_i = 1) \cdot P(R_i = 1|Y_i = y) + P(X_i = x|Y_i = y, R_i = 0) \cdot P(R_i = 0|Y_i = y)$$

Turning to the first term of the difference-in-means estimand, our selection process ensures by design that $P(R_i = 1|Y_i = 1) = 1$ and $P(R_i = 0|Y_i = 1) = 0$. Thus,

$$\begin{aligned} P(X_i = x|Y_i = 1) &= P(X_i = x|Y_i = 1, R_i = 1) \cdot P(R_i = 1|Y_i = 1) + P(X_i = x|Y_i = 1, R_i = 0) \cdot P(R_i = 0|Y_i = 1) \\ &= P(X_i = x|Y_i = 1, R_i = 1) \cdot 1 + P(X_i = x|Y_i = 1, R_i = 0) \cdot 0 \\ &= P(X_i = x|Y_i = 1, R_i = 1) \end{aligned}$$

Thus no correction for selection bias is required on the first term. Turning to the second term, our selection process ensures by design that $P(X_i = x|Y_i = 0, R_i = 1) = P(X_i = x|Y_i = 0, R_i = 0)$. Because of random selection, R_i is orthogonal to X_i. Thus,

$$\begin{aligned} P(X_i = x|Y_i = 0) &= P(X_i = x|Y_i = 0, R_i = 1) \cdot P(R_i = 1|Y_i = 0) + P(X_i = x|Y_i = 0, R_i = 0) \cdot P(R_i = 0|Y_i = 0) \\ &= P(X_i = x|Y_i = 0, R_i = 1) \cdot P(R_i = 1|Y_i = 0) + P(X_i = x|Y_i = 0, R_i = 1) \cdot P(R_i = 0|Y_i = 0) \\ &= P(X_i = x|Y_i = 0, R_i = 1) \cdot [P(R_i = 1|Y_i = 0) + P(R_i = 0|Y_i = 0)] \\ &= P(X_i = x|Y_i = 0, R_i = 1) \cdot 1 \\ &= P(X_i = x|Y_i = 0, R_i = 1) \end{aligned}$$

Thus no correction for selection bias is required on the second term. The difference-in-means calculations do not require weighting.

L.2 Regression estimands

L.2.1 Explanation for necessity of correction

In simplified form, the regression models try to predict lantern possession $Y_i = y$ based on binary covariate $X_i = x$. We can define the coefficient estimand as

$$\beta_x = P(Y_i = 1|X_i = 1) - P(Y_i = 1|X_i = 0)$$

However, we once again do not observe data for all households. Let R_i represent whether the observation was recorded (i.e., whether the household was selected for inclusion in the survey). We can thus rewrite

$$P(Y_i = 1|X_i = x) = P(Y_i = 1|X_i = x, R_i = 1) \cdot P(R_i = 1|X_i = x) + P(Y_i = 1|X_i = x, R_i = 0) \cdot P(R_i = 0|X_i = x)$$

By design, our selection process ensures that $P(Y_i = 1|X_i = x, R_i = 0) = 0$. Thus, we can simplify the expression

$$\begin{aligned} P(Y_i = 1|X_i = x) &= P(Y_i = 1|X_i = x, R_i = 1) \cdot P(R_i = 1|X_i = x) + 0 \cdot p(R_i = 0|X_i = x) \\ &= P(Y_i = 1|X_i = x, R_i = 1) \cdot P(R_i = 1|X_i = x) + 0 \\ &= P(Y_i = 1|X_i = x, R_i = 1) \cdot P(R_i = 1|X_i = x) \end{aligned}$$

where by design $0 < P(R_i = 1|X_i = x) < 1$. Thus, $P(Y_i = 1|X_i = x) \neq P(Y_i = 1|X_i = x, R_i = 1)$, implying that our selection process will bias estimands for β_x. We must correct for the probability of selection into the sample. We do so by introducing weights into the regression models reflecting $P(R_i = 1)$, which we defined solely based on Y_i, i.e., R_i is orthogonal to X_i given Y_i.

L.2.2 Generation of weights for correcting selection bias

We generated weights for the regression models based on the sampling strategy, defining weights as the inverse of probability of selection into the intended sample. Our sampling strategy selected matched households with probability one; all matched households therefore have weight one. To select unmatched households, we first subtracted the number of matched households from the total sample size. We then allocated the remaining sample across villages proportional to village size, defined as the number of households identified in the census exercise. In practice, the probability of selection for unmatched households was approximately 20%; unmatched households thus have weights of approximately 5 in the regression models. However, the probability and weights vary somewhat across villages owing to the necessity of rounding when allocating randomly selected households across villages.

Several caveats bear mentioning here. First, these probabilities and weights are based on the intended sample selection method. We deviated from this selection method in practice because some households were not available to be interviewed, resulting in data losses among matched households and in the selection of replacement households among unmatched households. Weights do not correct for deviation from the intended sampling strategy, which may introduce additional estimation bias. Second, the sampling method was based on our original matching algorithm, which simply selected the closest household to the maximum signal strength as the matched household for a given beacon sighting. After data collection concluded in its entirety, we replaced this algorithm with a more sophisticated one. We used the older matching algorithm to generate weights within the regression because we used the older algorithm to generate the household survey sample. In cases where a household was matched under the new algorithm but not the old algorithm, and where we happened to have collected data from the household via random selection, the probability of selection was still less than one despite its matched status. Finally, survey enumeration generated updates to the household census, as field staff identified some census buildings as labelled incorrectly for usage (e.g., a building labeled as a main household dwelling was actually an outbuilding for another household). Our original census thus slightly overestimated the number of households. However, sample selection used the original household census for sample allocation across villages. Thus, we use the uncorrected census information to generate selection probabilities and regression weights.