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Characterizing Informal Accessory Dwelling Units and Informing Housing Policy With Remote Sensing

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ABSTRACT

Problem, research strategy, and findings: One promising policy approach to addressing housing needs is liberalizing accessory dwelling unit (ADU) development. Yet, understanding the impact of such policy efforts is fundamentally constrained by the inability to quantify and characterize unpermitted ADUs, which may expose homeowners and tenants to legal, financial, and safety risks and confound policy evaluations. We addressed this gap by leveraging computer vision and human annotations to estimate the population of detached ADU constructions in San José (CA). Our contributions are threefold: 1) We estimated the proportion of unpermitted ADU constructions from 2016 to 2020; 2) we describe the demographic, housing market, and parcel characteristics associated with these informal ADUs; and 3) we provide a data set of labeled small buildings, excluding unpermitted detections, for further research. We found that informal ADU construction was substantial—*approximately three to four informal units for every formal unit*—and more likely in more diverse, dense, and overcrowded neighborhoods. Though our study was limited to analyzing detached ADUs during one time period, we set the stage for further investigations of informal housing across different typologies and over time.

Takeaway for practice: Our approach demonstrates the promise of computer vision and human annotations to enable more robust, comprehensive, and reliable understanding of actual—not just permitted—housing units. We urge planners and other policymakers to consider the growth patterns of unpermitted ADUs to more optimally and equitably address housing needs.

Keywords: accessory dwelling units, computer vision, informal housing, remote sensing, stratified sampling

For several decades, the United States has experienced a housing affordability crisis fueled by a chronic housing shortage. In 2020, 30% of households spent 30% or more of their household income on housing costs (Joint Center for Housing Studies of Harvard University, 2022). One solution recognized by state policymakers and championed by housing advocates is the development of accessory dwelling units (ADUs): independent, habitable structures that are added to an existing residential parcel (California Government Code §65852.150, 2019). Compared with detached single-family units, ADUs are less costly, faster to build, and allow for more flexible and diverse living arrangements (California Department of Housing & Community Development, 2022). With most residential zoning in the United States dominated by single-family use (Hamilton & Houseal, 2023), ADUs, typically added to single-family properties, offer a unique opportunity to overcome the resistance of local governments and homeowners toward increasing housing density, while providing homeowners with significant potential benefits such as rental income and, as of 2023 in California, separate sale (California AB 1033, 2023). ADUs are therefore considered a viable solution to the housing crisis by both advocates of top-down housing liberalization and (to a lesser extent) defenders of local exclusionary control, in that they are perceived to increase housing density while preserving the suburban landscape and cities' political status quo (California Department of Housing & Community Development, 2018). What is understood—and misunderstood—about ADU development patterns has significant bearing on the search for national housing solutions.

In recognition of ADUs' benefits, in the past few decades, at least eight states—California, Connecticut, Maine, New Hampshire, Oregon, Utah, Vermont, and Washington—have enacted legislation to liberalize ADU development and limit the constraints that local

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DOI: 10.1080/01944363.2024.2345730

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policymakers can impose (Hamilton & Houseal, 2023). However, despite these reforms, homeowners have continued to face barriers to permitting ADUs (Garcia, 2017; Healey, 2023). Beyond many restrictions that have been lifted, the continued existence of complex local permitting processes, hefty fees, restrictive regulations, and other barriers may discourage many property owners from pursuing an ADU permit. In fact, owners may still proceed to develop ADUs but *without* a permit (e.g., informally), exposing themselves and/or their tenants to potential legal, financial, and life safety risks.

Official data and prior literature have documented a significant expansion in permitted ADU construction in the past few years, most notably in California. Yet, any determination of the true extent of ADU growth would be incomplete without consideration of informal ADUs. Limited understanding of informal ADUs may also distort the assessment of the effects of ADU liberalization. For example, it is possible that recent ADU legislation has yielded less a net growth in housing and more a substitution effect, where ADUs that would have otherwise been built informally are instead built aboveboard. Moreover, any regressive effects of liberalization efforts could be missed, should they exist, where well-resourced residents can better take advantage of the benefits of permitted ADUs, whereas disadvantaged communities disproportionately bear the continued risks of informality.

We attempted to address this knowledge gap by leveraging computer vision and human annotations on a stratified sample to develop an unbiased estimate of the population of both formal and informal detached ADUs, which are distinct structures from the primary building on a parcel. This novel approach represents a substantial advance compared with existing literature: a) It overcomes the small sample size limitations of prior works relying on fieldwork and surveys, b) it produces unbiased estimates of informal housing units by enumerating detached ADUs directly from satellite imagery, and c) it produces sufficiently powered estimates via efficient sampling informed by a computer vision model. Using this approach in the city of San José (CA), we met two research objectives: 1) We estimated the composition of both formal and informal detached ADU constructions that took place during ADU liberalization in San José and 2) we differentiated them across demographic, housing market, and parcel characteristics. By considering informal detached ADUs, our estimates allowed us to paint a more accurate portrayal of ADU growth: its actual magnitude, its composition across formal and informal modalities, and its relationship to neighborhood characteristics. We also provide a labeled data set of small buildings from our study as a resource for future research, excluding informal detections.

Our study focused on the population of formal and informal detached ADUs during ADU liberalization in San José for several reasons. First, San José, home to about 1 million residents, is one of the largest cities in California, and the city's annual ADU applications, issued permits, and completed constructions have increased 30-fold since the onset of California ADU liberalization in 2016 (City of San José, 2023a). We provide further policy background on California and San José in Technical Appendix A. Second, as a large city, San José has public data readily available. We note that, due to the city's progressive local policy, our findings might be considered representative of a jurisdiction with a higher-than-average prevalence of formal ADUs and a more balanced distribution of formal and informal units across neighborhoods, relative to other cities across California with more restrictions on ADU growth. At the same time, higher construction costs, local housing pressures, demographic patterns, and other local characteristics in San José might result in a higher-than-average prevalence of informal ADUs.

We proceed as follows. First, we review existing literature on formal and informal ADUs and show that one of the most substantial challenges to understanding ADUs is the lack of available methods to generate unbiased and sufficiently powered estimates of unpermitted ADUs. Next, we present our approach of annotating satellite imagery from May 2016 and May 2020 to create an unbiased estimate of construction events in the period between (henceforth 2016–2020). The use of satellite imagery restricted our analysis to detached ADUs, but we argue that analysis of this ADU type meaningfully informed our understanding of the overall unpermitted rate. In the Results section, we present our estimates of the unpermitted proportion of detached ADU constructions during 2016–2020 in San José—approximately three to four informal units for every formal unit—along with descriptive analyses of the distribution of informal and formal constructions across neighborhood-level and parcel-level characteristics. Finally, we discuss key implications: for policymakers, how cities may rethink their approaches toward supporting ADU development and achieving affordable housing goals; for housing researchers, how our methodology and data release may enable more academic–public partnerships; and for code enforcement practices, how our approach should not be used to directly enforce unpermitted constructions but rather surface opportunities to address underlying barriers to legal construction.

Prior Literature on ADU and Informal Housing Growth

Our work relates to two streams of literature. We first examine prior works that have described the *formal*

ADU market and then review methods that have been used to measure and characterize the *informal* housing stock. Though ADUs are prevalent in other countries such as Australia and the United Kingdom—more commonly called *granny flats*—we limited the scope of our literature review to the United States and Canada. Table 1 describes representative works from each stream, including a single result from each work that most closely relates to our research objectives.

Formal ADU Market

Studies of the formal ADU market have relied on local building permits and certificates of occupancy. By nature, these studies produce a biased portrayal of a local ADU population. Moreover, these local administrative records can be prone to error, because they may not be fully completed by local planning departments.[1]

One method used in this stream of literature is surveys or interviews to homeowners who have previously applied for an ADU permit (Crane, 2020; Palmeri, 2014). These studies have identified that detached units comprise most formal ADU constructions: around 53% in California (Chapple et al., 2021) and 67% in Portland (OR), Seattle (WA), and Vancouver (Canada; referred to collectively here as PSV; Chapple et al., 2017). In PSV—cities with some of the most liberal ADU laws—respondents cited financing the development as one of their biggest barriers to building an ADU (Chapple et al., 2017). In California, the complexity of the permitting process and unclear regulations have also been highlighted in recent studies (Chapple et al., 2021; Greenberg et al., 2022), despite the passing of state-level ADU liberalization reforms since 2016. Surveys conducted on a more general population of homeowners have underscored these barriers to ADU development (Volker & Handy, 2023). Overall, survey-based studies have generally suffered from small and biased samples that limit the inferences that can be derived for the formal ADU population, let alone the population of unpermitted ADUs.

Past works have also used regression analyses of ADU permits/construction, typically to study the relationship between racial/socioeconomic status and formal ADU development in a specific region. In Seattle and King County, middle-income, Black, and Hispanic household concentrations exhibited a higher correlation with ADU permits (Maaoui, 2018). Although Chapple et al. (2020) reported similar trends for some jurisdictions in California, Marantz et al. (2023) found that there was no consistent relationship for counties in the Bay Area and Southern California. Other works have explored the impact of ADU liberalization laws on ADU development. Kim et al. (2023) found that in the city of Los Angeles, parcel and neighborhood characteristics became less correlated with formal ADU construction after liberalization, suggesting that these laws have had an effect in promoting formal ADU growth in new areas. However, because informal ADUs were excluded from this analysis, it remains unclear to what extent this formal ADU growth reflects an actual increase in ADU construction versus a substitution effect between informal and formal growth.

Informal Housing Market

The informal housing stock comprises housing units[2] that lack "proper building permits or land use approvals" (Wegmann & Mawhorter, 2017, p. 119). In addition to potentially overwhelming city services, these units may pose risks to their owners and inhabitants. By nature, these units have failed to undergo the proper building, fire, and health code inspections and may potentially constitute unsafe, substandard housing by failing to meet development and design ordinances (Bell, 2014a, 2014b). The consequences of these safety risks have been widely documented across California, most acutely in the form of fatal fires in converted garages and other spaces such as the Ghost Ship warehouse, which was being used as an unpermitted dwelling structure at the time of the 2016 fire, the deadliest to have taken place in Oakland (Bernstein, 1997; DeBolt, 2021; Healy, 2019; Tobar, 1996; Vives, 2014). Moreover, the potential disparate impacts of these safety consequences across population subgroups are concerning, given that "the key difference between unpermitted housing in affluent communities and disadvantaged communities is construction quality" (Bell, 2014b, p. 5). Informal units may also expose property owners to fines, legal action, and other consequences arising from noncompliance, and tenants face potential eviction from the dwelling unit (Wegmann & Bell, 2016). Financial institutions may be unwilling to extend financing on a property that includes unpermitted construction or to extend insurance coverage to unpermitted portions (Bray, n.d.; Galperin, 1995).

Due to the lack of reliable data on unpermitted housing units, the literature has resorted to three methods to measure the prevalence of informal housing. The first quantifies net unpermitted units by subtracting building permits issued in a jurisdiction during a period from housing stock change reported by national agencies (Baer, 1986; Brown et al., 2020; Crane, 2020; Gellen, 1985; Hardman, 1996; Wegmann & Mawhorter, 2017). An important limitation of this method is that national housing stock data may undercount informal housing units (Burgette et al., 2022; U.S. Census Bureau, 2019). Moreover, by using aggregate data, this methodology

Table 1. Summary of methods and representative works in the formal ADU market and informal housing market literature.

Literature	Location	Key result	Authors
Formal ADU market			
Surveys and interviews	Portland (OR), Seattle (WA), Vancouver (Canada; PSV)	Progressive ADU ordinances, fee waivers, and technical assistance for homeowners were key to ADU development in PSV	Chapple, Wegmann et al. (2017)
	California	Local approval processes, design requirements, and construction costs are homeowners' main barriers to building ADUs	Chapple et al. (2021)
	California	Development costs are the main challenge for low- and moderate-income BIPOC homeowners seeking to build ADUs and are exacerbated by limited financing options	Greenberg et al. (2022)
	Sacramento (CA) metropolitan area	Find significant homeowner openness toward building an ADU; construction and permit costs are the highest-ranked barriers	Volker and Handy (2023)
Regression and other statistical analyses of permit data	Seattle and King County (WA)	Concentrations of middle-income, Black, and Hispanic households are relatively more correlated with ADU permits	Maaoui (2018)
	California	Though there is regional variation within California in terms of income and ethnoracial composition, ADU construction generally takes place in areas with higher home values	Chapple et al. (2020)
	Los Angeles (CA)	Parcel and household characteristics are less correlated with ADU construction after ADU liberalization laws are passed	Kim et al. (2023)
	California	Find geographic variation in the neighborhood-level correlation between ethnoracial composition and ADU permitting	Marantz et al. (2023)
Informal housing market			
Analysis of the national or regional housing stocks	United States	Estimates that accessory apartments were added to the national housing stock at an annual rate of 95,000 to 120,000 units between 1973 and 1980	Gellen (1985)
	California	Find evidence of higher rates of informal housing production for lower-income cities between 1990 and 2010	Wegmann and Mawhorter (2017)
Identification of informal units from local data	Calgary (Canada)	Estimate and characterize the existence of 13,534 unauthorized secondary units in Calgary, as of 2015	van der Poorten and Miller (2017)
	Los Angeles (CA)	Finds evidence of the presence of an unpermitted secondary unit for 5.4% of a sample of 3,113 single-family home listings	Mukhija (2014)
	Southeastern Los Angeles (CA)	Finds that 9% of the residential built area in Southeast Los Angeles is noncompliant with lot coverage standards	Wegmann (2015)
Fieldwork, surveys, and visual inspections	Hamilton (Canada)	Estimates of the prevalence of secondary units can be derived from visual characteristics of single-family homes	Kinsella (2017)
	Unincorporated San Mateo County (CA)	Find that, on a random sample of parcels, 11.9% had an unpermitted ADU and 3% had a permitted ADU	Chapple, Abdelgany et al. (2017)
	Los Angeles County (CA)	Estimate the number of garages being used as dwelling units (3.2% of 500 single-family homes that were surveyed)	Chavez and Quinn (1987)
	Southern California	Find an inverse relationship between the prevalence of unauthorized dwelling units and income	Wegmann and Bell (2016)

cannot capture the neighborhood-level growth patterns of informal housing units that may inform more tailored policy responses.

The second methodology individually enumerates local housing stock data and identifies potentially informal units. Some works have linked housing data with building permit or land use data sets to detect housing units with noncompliant characteristics (Conrad et al., 2022; van der Poorten & Miller, 2017), whereas others have reviewed real estate listings (Mukhija, 2014). An essential limitation is potential data bias, which may arise from considering only advertised housing units or from capturing housing unit constructions based on irregularly updated tax appraiser information. There are works that have used highly detailed, annual census data for this purpose, such as van der Poorten and Miller (2017) for the city of Calgary (Canada), but such granular housing stock data are rarely available in cities in the United States and are expensive to maintain. Alternatively, researchers have used building footprint data and aerial photography to estimate the incidence of informal housing construction (Wegmann, 2014, 2015). Commonly available building footprint data, however, have important shortcomings, such as spatial variation in annotation detail and lower annotation rates for smaller, less-visible structures, that may inhibit the unbiased study of specific informal housing unit typologies like detached ADUs.

The third approach attempts to quantify the presence of formal and informal units in a location with fieldwork, surveys, and visual inspections of parcels (Chapple, Abdelgany et al., 2017; Chavez & Quinn, 1987; Kinsella, 2017; Wegmann & Bell, 2016). Although this methodology is more likely to capture an unbiased portrayal of the housing stock in a jurisdiction, its costly implementation usually results in small sample sizes and makes an understanding of demographic correlates difficult.

The two works most closely related to ours are Chapple, Abdelgany et al. (2017), whose fieldwork in unincorporated San Mateo County (CA) found an overall unpermitted rate of 75%; and Wegmann and Bell (2016), whose survey of code enforcement officers in Southern California revealed an inverse relationship between the prevalence of noncompliant units and median income. These two studies provided valuable benchmark estimates of the unpermitted proportion of ADUs that were relevant to our analysis for the city of San José. However, their methodologies were based on fieldwork and surveys to enforcement officers, which are limited by low sample sizes and possible biases from surveys, underscoring the need for a more robust and large-scale methodology.

Leveraging Computer Vision, Stratified Sampling, and Human Annotations

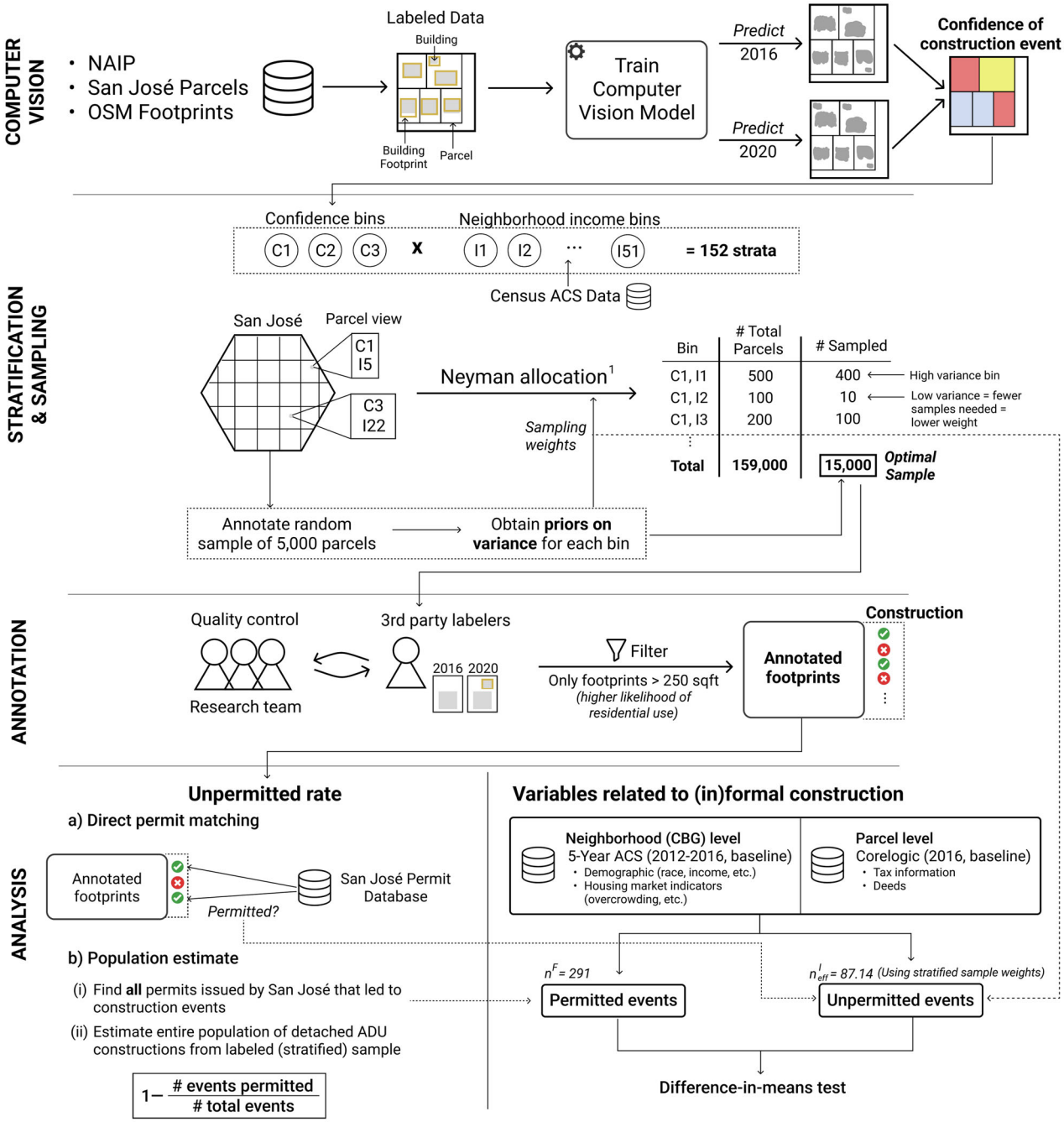
We designed our study to meet two objectives. First, we aimed to estimate the unpermitted proportion of all detached ADU constructions taking place during 2016–2020 in residential parcels in San José. Second, we aimed to estimate differences in demographic, housing market, and parcel characteristics between the formal and informal detached ADU constructions built during this period.

Overview of Methods

To answer these questions, we employed the following design, summarized in Figure 1. a) We trained a computer vision model to segment building footprints (see Technical Appendix C). We found that the computer vision model on its own was insufficient to quantify detached ADU construction events due to estimation errors, so we instead used it to b) construct 152 strata for categorizing parcels. These strata comprised 51 neighborhood income bins based on American Community Survey (ACS) data, as well as three bins of the computer vision model's confidence of an event (see Technical Appendix D.1). We chose this design with the goal of reducing the variance of the number of detached ADU constructions per parcel within each stratum, which in turn boosted the statistical efficiency of our downstream analyses. c) We employed Neyman allocation (Cochran, 1963) using priors (obtained from an initial simple random sample of 5,000 parcels) on the stratum-level variance of interest to optimally select a final stratified random sample of 15,000 parcels out of 159,000 total residential parcels in San José[3] (see Technical Appendix D.3). This sample was then d) labeled by third-party human labelers to indicate the existence of detached structures that appear habitable (see Figure 2 and Technical Appendix E). Finally, e) we used a subset of these hand-labeled annotations—those larger than 250 ft^2 and thus more likely habitable—to conduct our statistical analyses. Table 2 provides a description of all the data sets used in this study.

Statistical Analysis

We conducted two main analyses. First, we estimated the unpermitted proportion of detached ADU construction events during 2016–2020 using a) a global population estimate approach and b) a local permit matching approach. Population estimation in a) directly leverages the stratified sampling, aggregating the number of events in our sample from the strata level to the population level via a weighted sum (Cochran, 1963). We also obtained the estimate's variance, which was minimized by the Neyman allocation (see Technical Appendix D.2).



[1] A method that determines the optimal number of parcels to be sampled in each stratum that minimizes the variance of the population estimate. See Cochran (1953)

Figure 1. Flowchart of methods. See Technical Appendix Figure 1 for a more detailed description of methods used in this study.

This estimate was then compared to the number of detached ADUs permitted by San José. Meanwhile, in b) we rigorously linked each event detected in our sample to official permit records (City of San José Development Services Permit Center, 2023). We considered a parcel to have a permitted event if there exists any record of an ADU permit of any type during 2016–2020 (see Technical Appendix F.1). Both methods yielded an estimate of the unpermitted rate, which is

$$1 - \frac{\text{No. of permitted events}}{\text{No. of total events}}.$$

Second, we conducted difference-in-means tests between the parcels associated with formal and informal events. Concretely, we used $n^F = 291$ total formal events across all parcels in San José, which were derived from a list of 556 detached ADU permits issued during 2015–2020, filtering for permits that led to actual

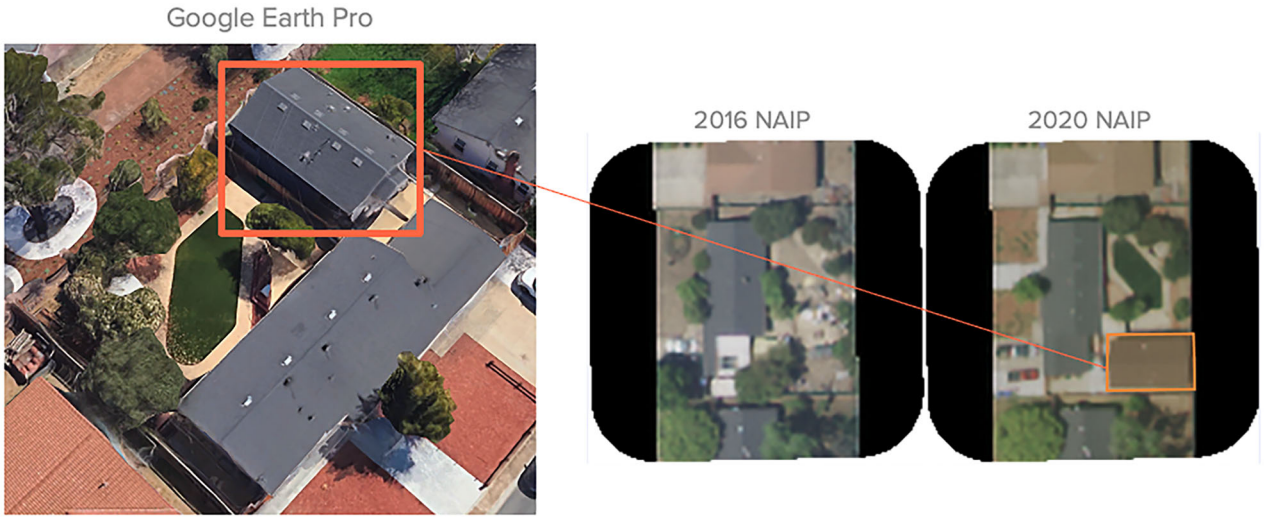


Figure 2. Example of a permitted detached ADU built during 2016–2020. On the left, a 3D visualization of the ADU and the parcel in which it is located using Google Earth Pro; on the right, the annotated National Agriculture Imagery Program (NAIP) imagery from 2016 and 2020 for the parcel, including an orange polygon around the ADU in 2020 (Google Earth, 2022; Earth Resources Observation and Science Center, 2022).

construction events within our study period (see Technical Appendix F). On the other hand, from our sample, we had $n^{I} = 146$ informal events, taken from our direct permit-matching exercise. Unlike the formal events, the informal events were derived from a stratified sample where parcels had unequal sampling probabilities. For this reason, we reweighted the informal events using the sampling weights from our Neyman allocation, resulting in an effective sample size of $n^{I}_{\text{eff}} = 87.14$ informal events. This is the size of a simple random sample that would have captured the mean of the distribution of informal events with the same level of precision. As a reminder, our stratified random sample was designed to optimize the efficiency of the population estimate in our first analysis by sampling parcels where we were most uncertain about the prevalence of events. This stratified sampling design, however, leads to correlated samples that have a lower efficiency than that of a simple random sample (but still yielding substantive results) for the purpose of our second analysis, characterizing the distribution of informal events. We compared both census block group–level (e.g., race, income, overcrowding) and parcel-level (e.g., assessed value, square footage) variables taken from the 5-year ACS (2012–2016) and CoreLogic (2016) data, respectively, reflecting conditions at baseline for our study. See Technical Appendix F.2 for further details.

Data Set Release

Our study yielded tens of thousands of images of residential parcels with positive or negative labels of small buildings, which may be useful for further research. However, some positive labels reflected unpermitted activity, and the release of such images, even if scrubbed of address information, may raise numerous ethical and privacy concerns (see Discussion). Our released data set excludes unpermitted detections (see Technical Appendix G).

Limitations

We now discuss several methodological limitations and how future efforts may build upon our work. First, given that we detected events from satellite imagery, we were limited to observing detached ADUs. It is worth noting that, according to a California-wide survey of formal ADUs, detached ADUs were the most common formal ADU typology in the state, representing 53% of 724 surveyed ADUs in 2020 (Chapple et al., 2021). Other typologies, such as garage or other building conversions (23%), attached ADUs (13%), and basement or other room conversions (9%), are usually less expensive to complete and easier to hide from view; therefore, we expected the unpermitted rate we estimated for only detached ADUs to be a lower bound on the overall unpermitted ADU rate. Nevertheless, understanding informality patterns across ADU typologies could help round out this picture.

Second, our annotation process potentially captured events that were not ADUs, such as guest houses or detached studios and home offices. Although annotators thoroughly attempted to determine structure habitability (see Technical Appendix E.1), distinguishing nonhabitable buildings from ADUs using imagery of the building exterior was often impossible. For this reason, our results could have overestimated the number of detached ADU constructions that took place during 2016–2020. However, we set a minimum threshold of 250 ft^2 for annotations to be captured as events to

Table 2. All data sets used in this study.

Data set	Description	Use
National Agriculture Imagery Program (NAIP) (Earth Resources Observation And Science Center, 2022)	NAIP publishes satellite imagery biannually for California at a resolution of 60 cm per pixel as of 2016. We used NAIP imagery captured in 2016 and 2020.	Training data for computer vision model (see Technical Appendix C.1)
OpenStreetMaps Buildings (OSM) (OpenStreetMap contributors, 2022).	OSM is an open-source database of building footprints. Though the data are not entirely reliable or up to date for certain neighborhoods, it remains the best source of publicly available footprints that also contains small habitable structures. We overlaid the footprints on NAIP imagery to train our computer vision model. Data were pulled in May 2022.	Training data for computer vision model (see Technical Appendix C.1)
American Community Survey (ACS) 5-year data (U.S. Census Bureau, 2016)	ACS conducts an ongoing annual survey of various socioeconomic and demographic characteristics throughout the United States, down to the census block group level. We used the 2012–2016 data to reflect variables at baseline of the study. See Technical Appendix D.1.	a) Categorizing parcels into neighborhood income bins for stratification b) Associating various neighborhood-level variables to parcels with (un)permitted construction events (see Table 3)
San José Accessory Dwelling Unit Permit database (City of San José, 2020)	List of 556 detached ADU permits issued during 2015–2020 that is maintained and was provided to us by the city of San José. Includes parcel APN, permit issue date, and property address.	Determining the total number of detached ADU constructions that took place between 2016 and 2020 ($n^F = 291$)
San José Permit & Property Information Portal database (City of San José, 2023b)	San José's online portal in which the permit history for a property can be searched for by parcel APN, property address, permit number, or property tract number.	Matching parcels in which we found a detached ADU construction to ADU permits (and to a more general set of permits for some robustness checks) listed on this portal for the parcel
San José parcel geodata (City of San José, 2021a).	Geocoded information of all parcels in San José, published by the city. Data were pulled in March 2022, which was last updated by the city in February 2021.	Matching building footprint data/predictions to their relevant parcels
San José zoning data (City of San José, 2021b).	Geocoded information of all zoning districts in the San José. Data were pulled in May 2022, which was last updated by the city in February 2021.	Filtering for parcels only in residential zones to which ADU laws apply
CoreLogic data (CoreLogic, 2016)	Comprehensive property data obtained by the company CoreLogic, which contains various real estate variables for each parcel in the United States over time, including land value, deed information, building square footage, etc. We used the data from 2016, which reflect the variables at baseline of our study.	Associating various parcel-level characteristics to parcels with (un)permitted construction events (see Table 3)

Note: APN = Assessor Parcel Number.

increase the likelihood that the remaining structures were large enough to contain the requisite features of habitability (i.e., a separate bathroom, kitchen, and sleeping area). We also included a robustness check (see Technical Appendix H.1) that further subsetted annotations to only those above 300 ft^2 and another (see Technical Appendix H.2) that linked constructions to a broader set of permits instead of only ADU permits, both of which supported our main finding.

Third, unpermitted ADU rates will undoubtedly vary among jurisdictions given differences in ADU ordinances, permitting processes, housing pressure, construction costs, and other local effects. Although one could draw many similarities among the conditions under which residents of different cities make ADU development decisions, we do not consider our findings for San José to be directly translatable to other cities or California at large. Nonetheless, our methodology can be replicated for individual cities (or even statewide).

Fourth, we were unable to draw causal inferences about the effect of ADU liberalization policies on the equitable permitting of ADUs. To make causal claims about the effect of a certain policy, one would need a control group in the experiment design—holding all

other factors constant—which is often infeasible to set up in the public policy setting. Our approach, however, did enable us to begin to assess the physical ordinance requirements that impede informal units from being built or legalized. In the Results section, we present a brief analysis of compliance with respect to minimum lot size requirements through time; this exercise could be extended to all the physical requirements that are specified in an ADU ordinance (e.g., maximum size, setbacks, distance to closest fire hydrant) through geospatial analysis. More generally, future work might also apply our methodology over multiple periods, say, before and after liberalization,[4] which would not constitute a causal analysis per se but may illuminate how construction patterns have changed for different populations over the period of liberalization.

Last, our methodology limits us from making any statements about the safety conditions in informal units. Unpermitted structures may not necessarily fail to comply with building codes and ordinance standards, but by nature these units have not undergone building, health, and fire code inspections. To assess safety conditions, future work may need to conduct field studies or rely on street inspections.

Results

Unpermitted Proportion of Detached ADU Constructions

We estimated a total of 1,336 ± 226 detached ADU construction events during 2016–2020 in San José. Given our estimate of 291 formal events in all of San José during the same period, we determined that 1,045 ± 226 events were *unpermitted*. Therefore, we concluded that 78.2% (74%–81% with 95% confidence) of detached ADU constructions during 2016–2020 were unpermitted. The permit-matching procedure corroborated this finding: We found that only 55 of the 201 events captured in our stratified sample matched to an ADU permit in the city's database, which translated to 74.7% (67%–82%) being unpermitted. The relatively tight bounds that we obtained for this result—requiring only annotation of 12.6% of all residential parcels in San José—speak to the efficiency of our computer vision–assisted stratified sample. We estimate that the computer vision model, by partitioning the universe of parcels into three confidence bins according to their likelihood of having an ADU construction, led to a 44.8% reduction in the required sample size compared with a stratification design informed only by neighborhood income (see Technical Appendix D.4).

We performed several types of robustness checks (see Technical Appendix H) to assess the sensitivity of this result to changes in our methodology and to produce more conservative estimates of this rate. First, using a stricter definition of detached ADU construction events, we found unpermitted rates of 67.0% via population estimation and 68.4% via permit matching. Raising the minimum square footage threshold of an event to 300 ft^2 resulted in an unpermitted rate of 71.3% via permit matching. Second, when using a broader set of permits to define the number of formal detached ADUs built during the period, we found an unpermitted rate of 71.8% via population estimation, whereas matching events to a more general set of permits from the city's database resulted in an unpermitted rate of 59.4% via permit matching. This could be interpreted as an unpermitted rate for all detached structures of any use or as an upper bound on the impact of miscategorizing formal detached ADUs as additions or alterations. Third, estimates via bootstrapping were almost identical to those via population estimation. These analyses point to an unpermitted rate that remained considerable under more conservative scenarios.

Indeed, we found that the approximately 1,045 unpermitted detached ADUs built during 2016–2020 help explain the gap between the number of new U.S. Census–reported housing units and the number of new city-reported dwelling units during the same period in San José. One-year ACS estimates (unavailable for 2020) indicated that San José had 9,879 more housing units in 2019 than 2016. Yet, using building permits finalized by the city between June 1, 2016, and June 1, 2019, we estimated an upper bound of 6,407 new formal dwelling units constructed contemporaneously (City of San José, 2023b). A large portion of the discrepancy could be reasonably explained by our unpermitted detections, which themselves only account for detached ADUs and not other ADU typologies.[5]

We also note that the informal events we found are distinct from structures that were built informally *prior to* 2016 (the start of our study period), legalized during 2016–2020, and thereby documented as formal detached ADUs. For reference, we identified 10 out of all detached ADU permits issued during 2015–2020 that were documented as legalizations of an existing detached structure, and thus excluded from our main analyses. Though our 291 formal detached ADU permits may include some misclassifications, most of these permits reflected new building constructions rather than legalizations.

Descriptive Analysis of Formal Versus Informal Detached Constructions

In addition to estimating the overall prevalence of informal detached ADU construction events, we investigated differences in the characteristics of formal and informal

Table 3. Difference in means tests across formal and informal detached ADU construction events.

	Formal events $n^F = 291$		Informal events $n^I_{eff} = 87.14$		
	Mean	***SE***	**Mean**	***SE***	***p*-value**
Neighborhood-level variables as of 2016					
1. Household median income ($)	96,885.9	2,007.9	89,765.6	4,042.1	.08
2. Number of households	574.5	16.8	595.9	30.7	.46
3. Median gross rent ($)	1,873.0	28.9	1,817.0	58.1	.30
4. Available housing vacancy rate (%)	0.9	0.1	1.0	0.2	.64
5. Percentage of renter occupied housing (%)	37.5	1.3	40.7	2.4	.18
6. **Hispanic or Latino population (%)**	34.0	1.3	42.7	2.8	<.01
7. **Non-Hispanic White population (%)**	32.4	1.4	26.5	2.5	<.01
8. Non-Hispanic Black population (%)	2.4	0.2	2.6	0.4	.60
9. **Non-Hispanic Asian population (%)**	27.2	1.2	22.8	1.9	.01
10. **Overcrowding (%)**	9.3	0.6	13.5	1.4	<.01
11. **Severe overcrowding (%)**	2.4	0.2	4.0	0.6	<.01
12. Households per square kilometer	1,172.5	28.9	1,173.7	57.9	.98
Parcel-level variables as of 2016					
13. **Assessed total value ($)**	537,047.9	18,644.6	429,996.9	29,749.0	<.01
14. **Assessed land value ($)**	326,391.0	13,560.3	238,767.9	21,139.7	<.01
15. Assessed improvement value ($)	211,434.2	8,209.5	191,229.0	13,202.0	.09
16. **Land square footage**	8,227.9	149.8	7,494.2	308.4	.02
17. Building square footage	1,537.6	32.4	1,511.7	53.3	.61
18. Bedrooms	3.2	0.0	3.3	0.1	.34
19. Homeowner exemption (%)	46.7	2.3	51.7	5.4	.32
20. **Years since last ownership change**	5.1	0.3	7.2	0.7	<.01

Note: Neighborhood-level (census block group) and parcel-level variables are derived from 5-year 2016 ACS estimates and CoreLogic property tax and deed data from 2016. Tests were computed on the 291 formal detached ADU construction events derived from the City of San José's permit database, and the informal sample comprises the 146 unpermitted events from our stratified sample (effective sample size of $n^I_{eff} = 87.14$ considering the sampling weights). Variables in **bold** reflect those with significant (at the 5% level) differences in the mean for formal and informal detached units.

events during 2016–2020. Table 3 compares the parcels containing these two populations across several neighborhood-level and parcel-level characteristics as of 2016, because the construction event itself may have affected many values in later years.

We found that homeowners who were more likely to build unpermitted detached units at the onset of ADU liberalization tended to be less wealthy (in terms of property value) and resided in neighborhoods with a lower proportion of White households, higher density, and greater overcrowding. Our robustness checks (see Technical Appendix H) retained the same significant relationships. Though existing studies have not compared the characteristics of formal ADU owners to those of informal owners, our result at minimum does not contradict or challenge prior findings that formal ADU construction in California has generally taken place in areas with higher home values (Chapple et al., 2020). Although our study could not make causal claims as to why these trends exist, we posit several mechanisms, including a) the perception of a complex ADU permitting process; b) difficult or constrained financing options, particularly for non-White groups; c) barriers of cultural assimilation, such as information gaps in immigrant communities regarding local building code and permit requirements; and d) zoning ordinances that disproportionately restrict ADU development options in certain communities due to physical characteristics.

To illustrate the last mechanism, we conducted a simple analysis of compliance of our formal and informal events based on one restriction: minimum lot size. As presented in Table 4, we observed that 18.5% of the informal events occurred on parcels that would not have been compliant with the 5,445 ft^2 minimum lot size required by the ordinance prior to July 2018, assuming they were built prior to this date. This finding suggests that relaxing minimum lot size constituted a liberalization that, on one hand, might have enabled some homeowners to have pursued their projects legally. On the other hand, even if a relaxed minimum

Table 4. Compliance of formal and informal detached ADUs with minimum lot size.

	Before July 2018	July 2018–December 2019	After December 2019
Ordinance minimum lot size requirement (ft^2)	5,445	3,000	No minimum
Number of detached ADU permits issued (from the population of 291 formal detached ADUs during 2016–2020)	115	166	10
Percentage of formal detached ADUs not in compliance (with the operative minimum lot size requirement at permit issuance) ($n = 291$) (%)	0	0	0
Percentage of informal detached ADUs (built anytime during 2016–2020) that **would not have been** in compliance ($n = 146$) (%)	18.5	0	0

Note: City of San José ADU ordinance requirements on minimum lot size and compliance of formal ADUs (top) and percentage of the 146 informal detached ADUs that would not have been in compliance with this requirement over time (bottom). Ordinance updates took place on July 27, 2018, and December 17, 2019. Because we did not observe exactly when our annotated 146 informal events occurred, we only present the proportion that would not have been compliant across each version of the city's ADU ordinance.

lot size would not have affected the original decision to build informally, it at least unlocked the opportunity for legalization in the future.

Discussion

Our stratified random sampling of 15,000 residential parcels in San José yielded 201 high-quality annotations of detached ADU construction events from 2016 to 2020, most of which we determined to be unpermitted events. Using population estimation and permit-matching approaches, we estimated an unpermitted rate of 78.2% or 74.7%. In other words, for every one formal detached ADU built during this period, an estimated three to four informal detached ADUs were also built. Under a range of different assumptions we checked for robustness, our unpermitted rate did not fall below 59%, which still reflects *at least* three informal events for every formal two. We also found that homeowners in less wealthy, higher density, and minority communities were more likely to build unpermitted detached ADUs and that many of these homeowners may have experienced explicit zoning restrictions as one barrier to building aboveboard. Furthermore, we provide a large data set of labeled small buildings—excluding those we determined to be unpermitted—as a resource for future research. We now present three key implications from our demonstration.

Implications of Informal Rate for Housing Policymakers

We believe the quantity of recent informal ADUs in San José was far higher than conventional wisdom among policymakers and the media would assume. This substantive finding, however, roughly aligns with prior works that have attempted to quantify the informal ADU stock via surveys and fieldwork elsewhere in California. In particular, Chapple, Abdelgany et al. (2017) suggested an unpermitted rate of 75% for all ADU types in unincorporated San Mateo County as of 2017. This measure considered the entire population of housing units at a point in time, rather than, as we did, the population of construction events over a time period; nevertheless, if we assume our estimated unpermitted rate for detached ADUs built during 2016–2020 has largely stayed constant through time,[6] our estimate is quite similar in magnitude.

The scale of unaccounted-for housing we found in San José poses some intriguing questions about how people react to a perceived housing shortage. Perhaps we have underestimated the degree to which communities may assert agency in the absence of policy solutions and thus undervalued the risks many households take in building informal housing to avoid the shock of displacement or homelessness. ADU liberalization efforts therefore may need to focus more on increasing access to the benefits of formal permitting where barriers have disproportionately prohibited certain groups.

This unaccounted-for ADU construction also has important implications for how cities achieve their housing targets, particularly for affordable housing. The city of San José's official count of 6,689 completed new dwelling units of any kind between June 1, 2016, and June 1, 2020, excludes approximately 1,045 *unofficial* detached ADUs, not to mention other unpermitted ADU typologies (City of San José, 2023b). In other words, San José's reported progress toward state-mandated housing goals during this period could have been 15% higher, had all of these informal units been built aboveboard. This framing is particularly important, given that a) the city of San José has only met 26% of its affordable housing goal for the current Regional Housing Needs Allocation cycle, as of writing (Burton & Morales-Ferrand, 2023), and b) ADUs are well established as contributors to affordable housing supply

(California Department of Housing & Community Development, 2022). Therefore, lowering the barriers to permitting ADUs and legalizing unpermitted ADUs may be far easier pathways to achieving affordable housing targets than planning for new developments of affordable housing, though the efforts need not be mutually exclusive.

Although our study alone could not assess whether the city had made substantive progress on these fronts, we hope our study sets the stage for future work that can replicate our approach on prior or subsequent time periods to evaluate changes over time, in San José and beyond. Encouragingly, recent California law has continued to explore new ways to address barriers to formal ADU development, particularly in 2022 with more streamlined permit approval processes and retroactive permitting for unpermitted ADUs built before 2018 (California A.B. 2221, 2022; California S.B. 897, 2022). Several jurisdictions, including the city of San José, have already adopted amnesty programs that offer technical—and, in some cases, financial—support for homeowners who wish to legalize their unpermitted ADUs.

Implications of Our Methodology for Housing Researchers

As discussed above, our methodology of labeling an efficiently allocated, stratified sample of parcels tackles various challenges from previous works on ADUs and informal housing, such as the use of biased data and analyses on small sample sizes. Our method can be tailored according to a specific statistical analysis or annotation budget and can scale well to other mid-sized to large cities throughout the United States. Although most local governments are unlikely to have the resources or expertise in-house to conduct these analyses, we believe they will have increasing access to the services of housing researchers who can.

Our successful use of a third-party annotator to label detached ADUs from satellite imagery serves as a proof of concept that housing researchers can emulate for larger-scale studies. As demand for data labeling in the artificial intelligence industry has substantially expanded in recent years, companies providing these services have grown in quantity and reputation, making this type of assisted research more accessible ("Data-Labelling Startups Want to Help Improve Corporate AI," 2019; Murawski, 2019).

Moreover, we have demonstrated that our method's use of a computer vision model to provide signals on detached ADU construction activity allows for much more efficient sampling, as estimated by a 44.8% reduction in the required sample size compared with a stratified sample informed only by neighborhood income (see Technical Appendix D.4). We expect this to be highly beneficial to researchers seeking to apply this methodological framework, particularly as satellite imagery becomes increasingly available at higher resolutions and computing becomes increasingly accessible. As such, we hope that local governments, in partnership with researchers, may use our framework to pursue other questions about informal ADUs.

Finally, to assist housing researchers in developing improved computer vision models in this domain, we have released a data set featuring more than 2,000 labeled images of small buildings (excluding those we deemed sensitive) that resulted from our extensive annotation process (see Technical Appendix G).

Implications of Our Methodology and the Use of Satellite Imagery for Code Enforcement

A crucial consideration in conducting this study was the extent to which satellite imagery can and should be used for code enforcement. The city of San José—as well as most local governments in California—currently practices a community-driven, responsive approach whereby enforcement is triggered when the code enforcement office is notified of a potential unpermitted ADU, usually through complaints. Using the city's code complaint data during 2016–2023 (City of San José, 2023c), we estimated a general complaint rate per parcel of 5.3% for the parcels in which the 146 informal events occurred (see Technical Appendix I). Local officials therefore cannot expect to substantively address the risks of informal units by relying exclusively on complaint-based code enforcement.

However, our work should not be misconstrued as being a proof of concept or endorsement for local governments to enforce code more thoroughly using satellite imagery. We followed procedures to protect the anonymity of the likely unpermitted events we detected in our sample—including presenting only aggregate statistical results and releasing data that exclude parcels with unpermitted observations—like prior works that have generated sensitive data sets of this nature (Conrad et al., 2022).

Image-based enforcement raises many ethical, legal, and privacy concerns. For example, in 2010, the use of Google Earth imagery by the town of Riverhead (NY) to detect and levy up to $75,000 in fines for unpermitted backyard swimming pools was perceived as an overstep on local government authority and generated considerable controversy and national press coverage (CBS News, 2010). Code enforcement offices throughout the United States are increasingly considering the use of satellite imagery *for reference only* before conducting physical inspections (County of Lake, 2021; Driscoll, 2019; Missouri City, 2013). Though reviewing all or even a random

subset of parcels in a mid-sized to large city is likely beyond the capacity of local code enforcement offices, the increasing power of artificial intelligence tools could expand the ability of governments to conduct direct image-based enforcement. As these technologies become more widespread, legal cases surrounding building code enforcement will undoubtedly arise, as public perception and normative policy will also evolve.

Another concern is the delicate line that enforcement should carefully tread with the knowledge that unpermitted detached ADUs are more likely to be built in less wealthy and more diverse neighborhoods. On the one hand, conducting an enforcement strategy that disproportionately targets less-advantaged homeowners—those who have the most to lose from hefty fines and who likely face the greatest barriers to getting their constructions aboveboard in the first place—may be viewed as unfair and unproductive, even exacerbating distrust in local governance. On the other hand, complaint-driven enforcement may propagate disparities in risk exposure and citizen complaint propensity. Using the city's code complaint data for 2016–2020, we found that there is a significant difference ($p < .001$) in the mean census block group–level income between parcels that were and were not associated with issued complaints, corresponding to $85,000 and $105,000, respectively. Thus, maintaining the status quo enforcement regime may entrench its own forms of inequity.

As a compromise, we hope that our approach is used to inform the design of equity-driven policies that focus on *communities* rather than specific noncompliant homeowners and generate *supportive resources* rather than disciplinary actions. These may include initiatives such as outreach programs, ADU amnesty programs, and permit process improvements. Cost is likely a dominant barrier that drives homeowners toward informal ADU development. In the city of San José, fees related to permit issuance, plan review, and inspections currently stand at approximately $3,000 to $4,700; reducing or waiving such fees for low-income households may be the simplest way to encourage permitting. Ultimately, local enforcement should strive to directly address the underlying barriers to legal ADU construction, rather than the symptoms stemming from these barriers.

Toward a More Complete Understanding of ADUs

Overall, we have developed a rigorous, cost-effective, and flexible methodological framework that enables the measurement and characterization of the complete detached ADU stock. This framework has allowed us to compute a robust estimate of the relative prevalence of informal detached ADU constructions in the city of San José during 2016–2020—approximately three to four informal units for every formal unit—and to describe where these informal units were built, namely, in more diverse, dense, and overcrowded neighborhoods.

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ACKNOWLEDGMENTS

We thank Kip Harkness, Rachel Roberts, Oscar Carrillo, Joseph Hatfield, and Molly Regan from the City of San José for their partnership and input; Kit Rodolfa, Muhammad Alameldin, Caleb Smith, Bryce Nesbitt, Duane Bay, Iliana Nicholas, and Karen Camacho for helpful comments and conversations; and the Housing Solutions Lab at NYU Furman Center for providing valuable feedback.

DATA AVAILABILITY STATEMENT

The data and code that support the findings of this study are openly available at github.com/reglab/informal-adus.

RESEARCH SUPPORT

This work was supported by the Housing Solutions Lab at the NYU Furman Center for Real Estate and Urban Policy, New York University.

SUPPLEMENTAL MATERIAL

Supplemental data for this article can be found at https://doi.org/10.1080/01944363.2024.2345730.

NOTES

1. However, given the scale of unpermitted events we estimated in this study, incorrectly recorded formal events are likely

negligible in their impact on the relative proportion of formal versus informal events.

2. The definition of a housing unit varies across different works depending on their methodology, but in its most general form aligns with that of the U.S. Census Bureau: a house, an apartment, a mobile home, a group of rooms, or a single room that is occupied or intended for occupancy as separate living quarters (U.S. Census Bureau, Population Estimates Program, n.d.).

3. Of approximately 224,000 parcels in San José, we defined residential parcels to be those in R-1 (single-family residence), R-2 (two-family residence), or R-M (multiple residence) zoning districts, based on 2022 data, that are also less than 5,000 square meters in size.

4. National Agriculture Imagery Program (NAIP) imagery for 2022 has been published since the conclusion of our analyses and could be used to produce population estimates for 2020–2022.

5. The number of housing units reported in the ACS may itself be undercounted. Also, San José's administrative boundaries registered only a small increase during the period (1% rise in land area from 2010 to 2020), limiting the possibility that this deficit can be explained by annexed housing units.

6. One might in fact interpret our estimate to be a lower bound of the whole population given the sweeping reforms to liberalize ADUs during this period, but it remains unclear whether such liberalization has reduced the unpermitted rate.

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