
Foto: Ana Paula Hirama

The Skyscraper Revolution: Global Economic Development and Land Savings

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Outline

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  Exponential growth in global aggregate building height since 1975

  - Much in developing economies
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  - Urbanization: Allow cities to accommodate more people
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- Literature: Analogous studies on effects of urban transportation infrastructure (highways, subways, railroads, etc.)

  - Key complication is that skyscraper construction is more closely tied to fundamental local demand and cost factors.

Our Analysis

- Global panel data analysis
  - Novel database: 12,877 world cities (90% world's urban pop) in 1975 (1990, 2000) & 2015. RHS: tall building stock; LHS: pop, area
  - Emporis: data on all tall buildings ($\geq$ 55 meters) ever built worldwide, with construction year and (sometimes) cost info

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  - Larger cities in 1975 had greater demand for height
  - Secular decline 1975-2015 in the marginal cost of building taller
  - Bedrock depth influences cost of installing foundations.
    If too close to the surface, bedrock must be blasted away.
    If too deep, foundations not anchored, must be reinforced.

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- Model: Tall buildings could increase global welfare by 4.8%. But only 1/4 has been realized likely due to land-use constraints

Literature

1. Infrastructure

   Baum-Snow '07, '20, Duranton & Turner '12, Faber '14, Heblich et al '20, Brooks et al '21, Campante & Yanagizawa-Drott '18, Alsan & Goldin '19

2. Economics of density

   Combes & Gobillon '15, Ahlfeldt & Pietrostefani '19, Duranton & Puga '20 for surveys; Rosenthal & Strange '08 and Combes et al '11 for geological IVs

3. Sprawl

   Burchfield et al '06, Henderson et al '18, Harari '20, Gollin et al '21

4. Housing Supply and Urban Development

   Baum-Snow & Han, '24, Bertaud & Brueckner '05, Henderson et al '21, Brueckner & Sridhar '12, Brueckner et al '17, Tan et al '20, Jedwab et al '20

5. Economics of skyscrapers

   Barr '10, '12, Barr et al '11, Ahlfeldt & McMillen 2018, Liu et al '18, '20, Ahlfeldt & Barr '20, '22, Jedwab et al '20, '21, Jedwab & Barr '22, Jedwab '22, Curci '22

Outline

Data

- Sample: 12,877 50K+ agglomerations* today (*urban centres* from GHS)
- City-level outcomes:

  From GHS, pop, built-up area and land area 1975 (1990 2000) & 2015

  Radiance calibrated version of the DMSP night lights 1996-2011**

  Global land change data 1982-2015 (deforestation, cropland, etc.)

- Main variable of interest:

  From *Emporis*, location, height ($\geq$ 55 meters) & year of construction

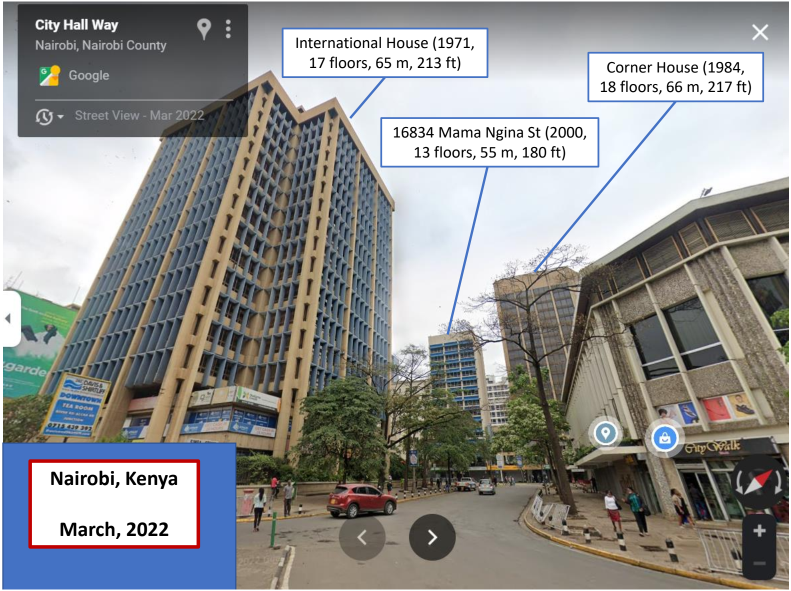
  Information provided by industry. "*Emporis collects information about the full life-cycle of each building, from idea to demolition*"

  Tall building stocks (km) for each city 1975 (1990 2000) & 2015

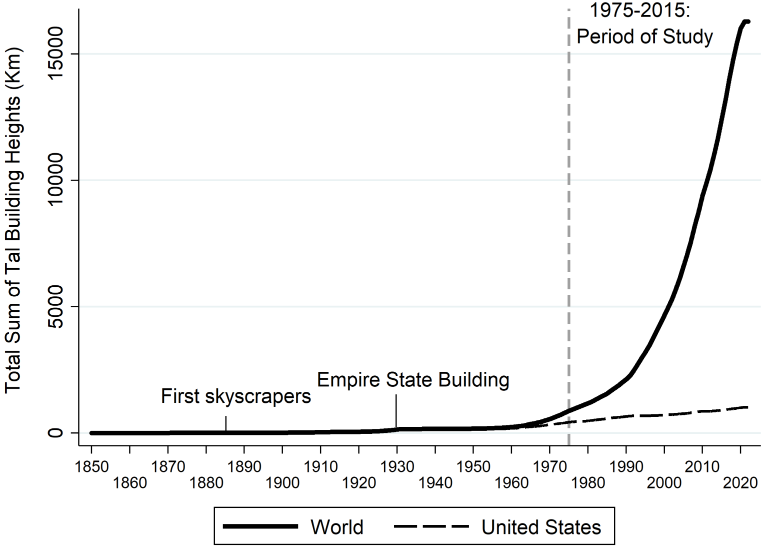
* Urban centres correspond to commuting zones. For example, New York UC includes "New York; Islip; Newark; Jersey City; Yonkers; Huntington; Paterson; Stamford; Elizabeth; New Brunswick"

** Radiance calibrated = NOT top coded at 63.

Examples of Concrete Tall Buildings ($\geq$ 55 m $\approx$ 165 ft)

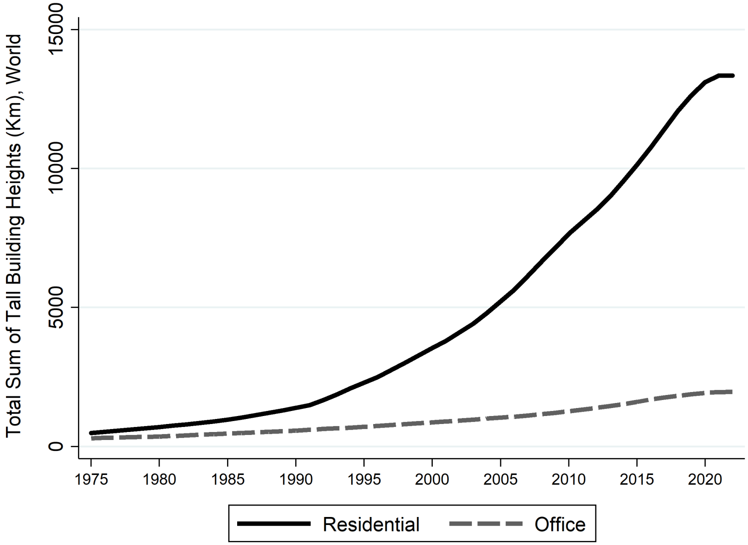


The Global Stock of Tall Buildings



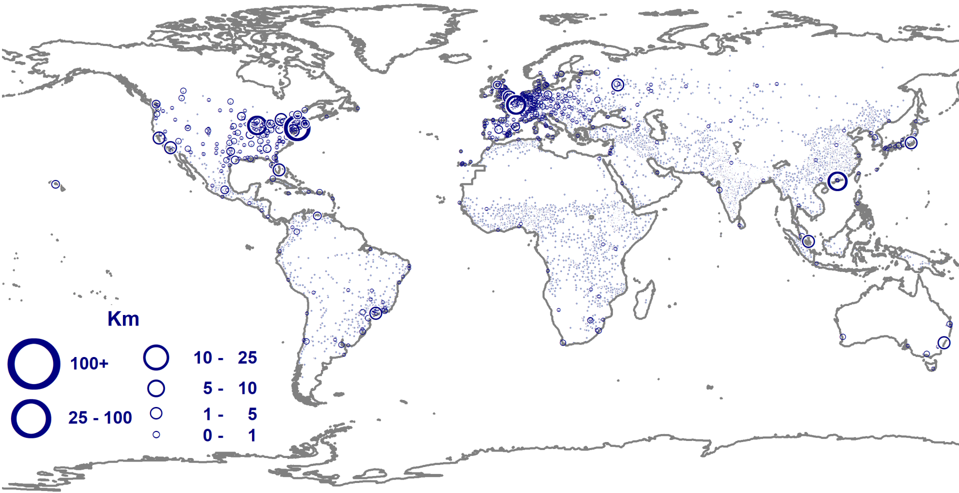
Includes all buildings ≥ 55 meters, ≈ 14 floors. 1975-2015: +11,500 km ≈ 26K Empire State Buildings ≈ 3x Euclidean distance between NYC and LA!

Most Recent Tall Building Construction is Residential



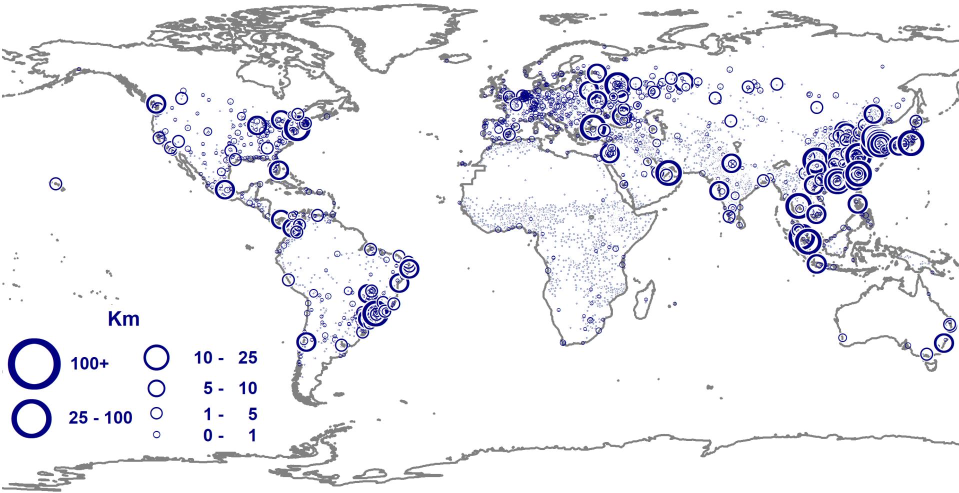
World of residential towers: Increased 7x more for residential buildings (typically in the 55-100 m range) than for commercial/office buildings (100 m+).

The Stock of Skyscraper Heights in 1975



Historically, global skyline dominated by North America & Western Europe

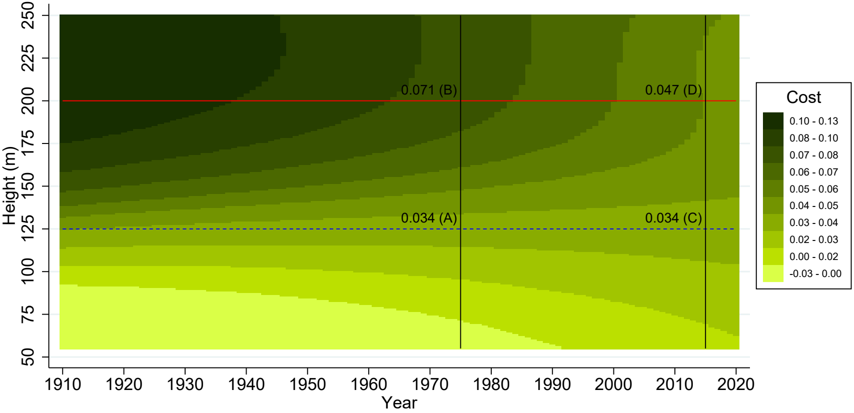
The Flow of Skyscraper Heights 1975-2015



Rising skylines in Asia, the Gulf, Latin America & Eastern Europe

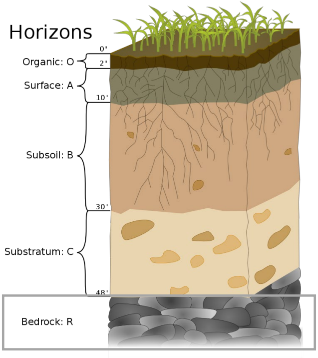
Cost of height decreased over time

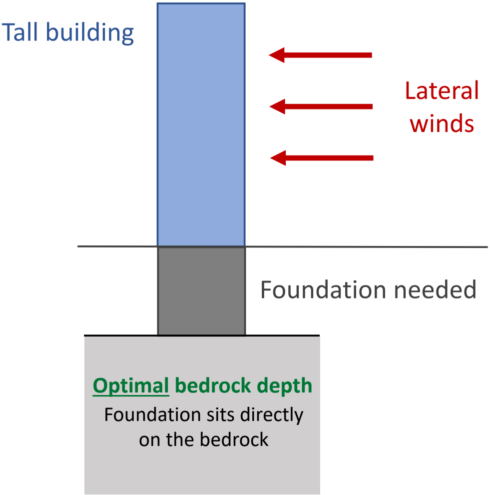
- 600 U.S. tall buildings for which construction cost in Emporis
- Log cost per sq ft residualized for city FE and decade FE



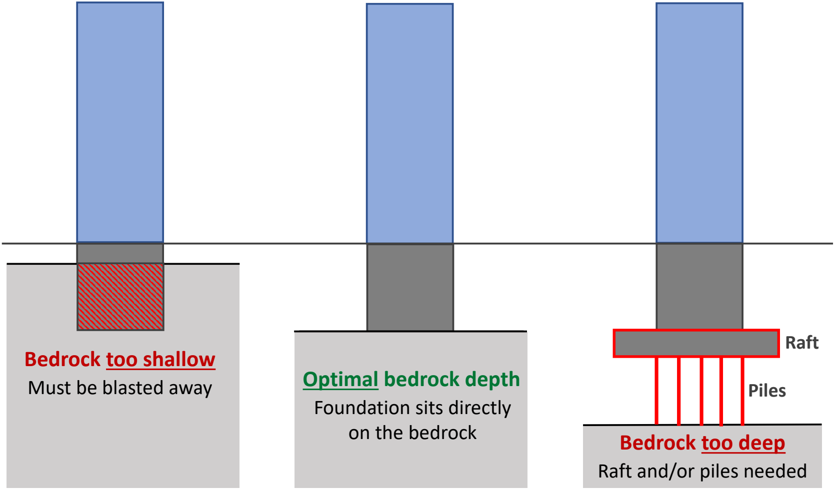
Cost per sq ft for 200m vs. 125 m $\approx +4\%$ in 1975 vs. $+2\%$ in 2015

Role of Bedrock I (needed to build the identification strategy)



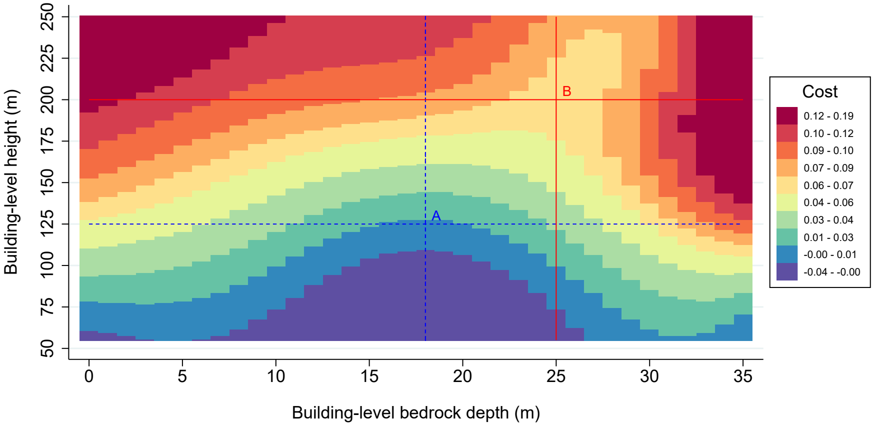


Role of Bedrock II (needed to build the identification strategy)



Inverted-U Relation btw Cost of Height & Bedrock Depth

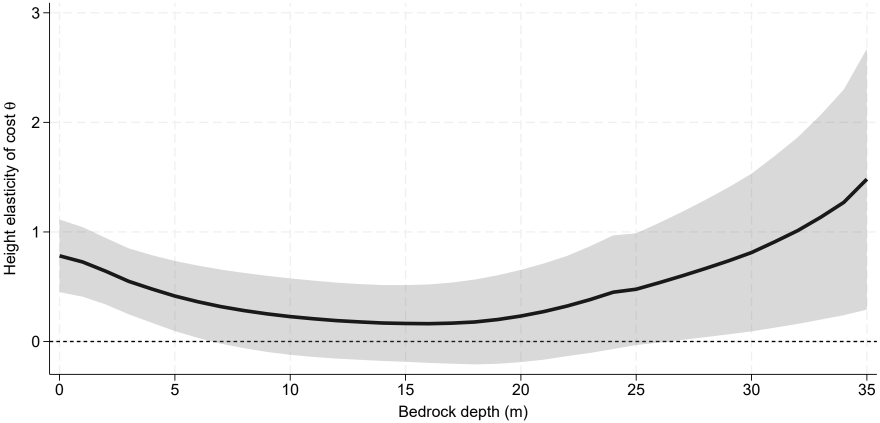
- 1,033 tall buildings with construction cost (206 cities in 55 countries)
- Log cost per sq ft residualized for city FE and country-decade FE



At 125 m, optimal depth saves $> 5\%$ in cost per sq ft relative to surface level or very deep bedrock. Cost savings much larger for 200 m tall buildings ($> 10\%$).

Marginal Cost Minimized at Intermediate Depths

- Estimate height elasticity of unit cost (θ) across all building heights*
- Easier to accommodate real estate demand at intermediate depths



* We predict height using distance from the city center as a demand-side IV

The Cost Function for Height

City a in country c in year t:

The total variable cost of building to height S is:

$$C_{act}(S) = c_{act} S^{1+\theta(B_{ac},\psi_t)}$$

θ is U-shaped in bedrock depth (foundation costs)

θ declining over time (due to worldwide technological progress ψ_t)

c_{act} city-year specific cost shifter

Profit Maximization: The Muth Model Revisited

- A representative developer's profit function is:

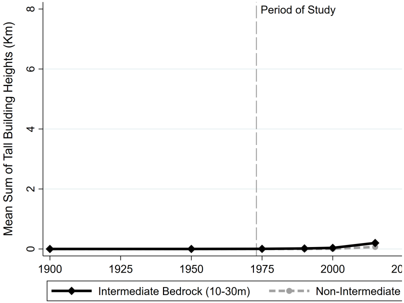
$$\pi_{act}(S, x) = \int_0^S p_{act}(x, s)ds - C_{act}(S) - r_{act}(x).$$

- We use the demand structure $p_{act}(x, s) = p_{act}(x)s^{\omega}$
- Resulting equilibrium height supply at location x is:

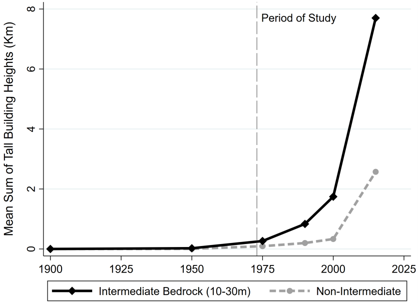
$$\ln S^* = \frac{1}{\theta(B_{ac}, \psi_t) - \omega}\left(\ln \frac{p_{act}(x)}{c_{act}} - \ln\left[\theta(B_{ac}, \psi_t) - 1\right]\right)$$

- For a higher level of p/c (larger 1975 pop, hence demand for height), there is a bigger effect of θ on supplied height:
  - Decline in μ_t (technological progress) grows height more
  - Bedrock depth B_{ac} matters more

Bedrock Depth & Mean Sum of Heights Over Time



Small Cities ≤ 300K in 1975

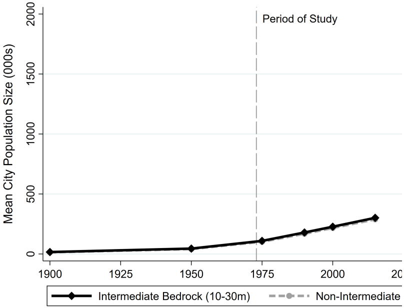


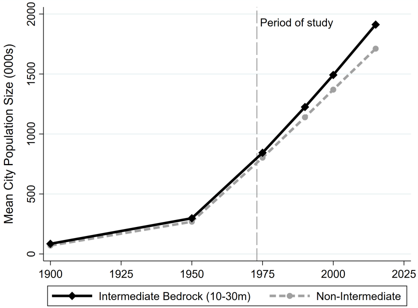
Large Cities ≥ 300K in 1975

Sample: 1,748 developing country cities in pop database of Buringh et al

300K ∼95p in pop in 1975, selects 418 cities among top 500 today

Bedrock Depth & City Pop Over Time





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A Triple DiD Empirical Strategy

- Conditional on bedrock depth, initially larger cities (as of 1975) have experienced greater 1975-2015 growth in heights.
- However, the strength of the relationship between city size and height growth should depend on bedrock depth in the city.

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- However, the strength of the relationship between city size and height growth should depend on bedrock depth in the city.
- For mean bedrock in each 5 meter depth range b, estimate construction 1975-2015 in 12,869 cities a conditional on 179 country c FE:

$$Const_{ac} = \gamma_{b(ac)} \ln Pop_{ac75} + \delta \ln Pop_{ac75} + \kappa_c + \phi_{b(ac)} + \epsilon_{ac}$$

Const_{acb} is 1975-2015 change in log aggregate building heights or an indicator for any tall building construction in city ac on a 0 base

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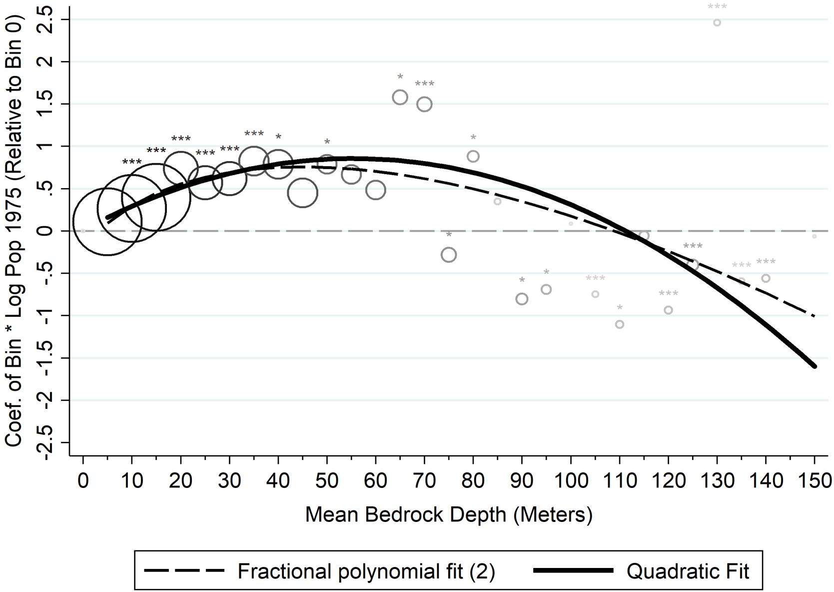
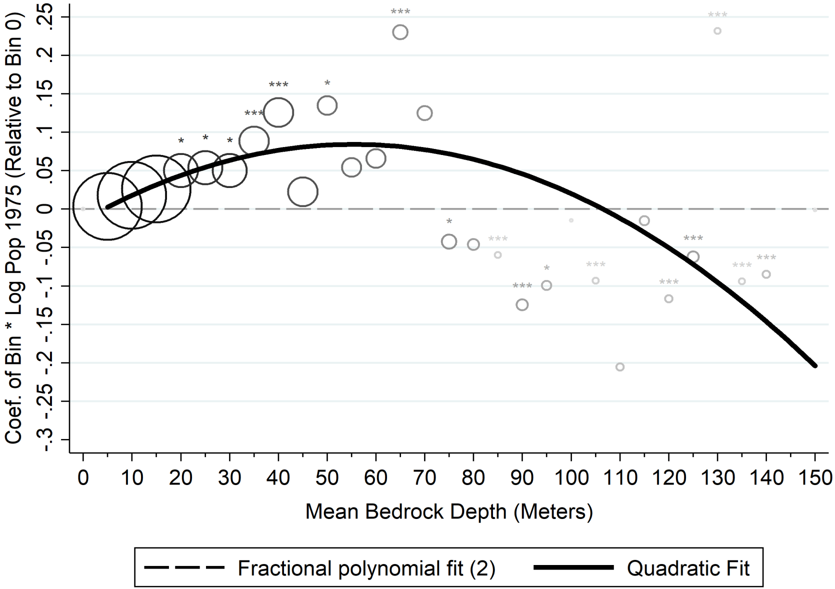
- Consistent with engineering discussion above, estimates of γ_b are greatest for intermediate bedrock depths

Elasticities of Tall Building Height Growth 1975-2015 wrt *1975 City Population by Bedrock Depth*



Elasticities of Tall Building Constr. Dummy 1975-2015 wrt *1975 City Population by Bedrock Depth*



An IV Strategy for City Height Growth

- Data generating process for heights in city *a* and country *c*:

$$
\begin{aligned}
Const_{ac} = k_1 MBD_{ac} + k_2 MBD_{ac}^2 + \delta \ln Pop_{ac75} \\
+\gamma_1 MBD_{ac} \times \ln Pop_{ac75} + \gamma_2 MBD_{ac}^2 \times \ln Pop_{ac75} + \\
+X_{ac75}\xi + \kappa_c + \epsilon_{ac}
\end{aligned}
$$

- Identifying variation has a diff-in-diff flavor: intermediate vs. extreme (too shallow or too deep) bedrock AND high vs. low initial pop (1975)

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- Identifying variation has a diff-in-diff flavor: intermediate vs. extreme (too shallow or too deep) bedrock AND high vs. low initial pop (1975)
- A valid IV must plausibly hold trends in city demand factors constant:
  - Time-invariant city effects captured by first difference.
  - As larger cities have different trends in demand for height than smaller cities, we must control for 1975 city population.
  - To allow for the possibility that cities with different bedrock depths are on different trends, we must control for bedrock depth.

First Stage Estimates (3rd Column)

	Δ ln Height 1975-2015		
ln Pop 1975	0.8730***	0.8741***	0.4753***
	[0.0351]	[0.0351]	[0.0653]
Bedrock Depth		-0.0028*	-0.3248***
		[0.0016]	[0.0612]
$(\text{Bedrock Depth})^2$		0.0000	0.0021**
		[0.0000]	[0.0009]
Bedrock Depth			0.0276***
X ln Pop 1975			[0.0054]
$(\text{Bedrock Depth})^2$			-0.0002**
X ln Pop 1975			[0.0001]
Country FE	Y	Y	Y
R-squared	0.17	0.17	0.18
Observations	12,869	12,869	12,869

Faster height growth in initially larger cities X intermediate bedrock.

The Change as a Final Level: Log Heights 1975 vs. 2015

	1975	2015	Δ 1975-2015
		Panel A: All Countries	
Bedrock Depth	0.0126***	0.0402***	0.0276***
× ln Pop 1975	[0.0032]	[0.0062]	[0.0054]
(Bedrock Depth)^2	-0.0002***	-0.0003***	-0.0002**
× ln Pop 1975	[0.0000]	[0.0001]	[0.0001]
R-Squared	0.18	0.33	0.18
		Panel B: Developing Economies	
Bedrock Depth	0.0030	0.0292***	0.0262***
× ln Pop 1975	[0.0028]	[0.0060]	[0.0056]
(Bedrock Depth)^2	-0.0000*	-0.0002**	-0.0002**
× ln Pop 1975	[0.0000]	[0.0001]	[0.0001]
R-squared	0.14	0.29	0.22

Developing econ: Little height in 1975 $\rightarrow$ g(bedrock,pop75) irrelevant

IV Regresssion Specification

- Main estimation equation (N = 12,869 cities a in 179 countries c):

$$y_{ac} = \beta \Delta \ln \left(Heights_{ac} + 1 \right) + \alpha_1 MBD_{ac} + \alpha_2 MBD_{ac}^2 \\ + \alpha_3 \ln Pop_{ac75} + \kappa_c + \varepsilon_{ac}$$

- Outcomes are 1975-2015 city level growth rates of
  - Population
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- Outcomes are 1975-2015 city level growth rates of
  - Population
  - Built-up area
  - Population density
- First-differences capture city effects. We also add country FE.
- Instrument for $\Delta \ln \left(Heights_{ac} + 1 \right)$ with $MBD_{ac} \times \ln Pop_{ac75}$ and $MBD_{ac}^2 \times \ln Pop_{ac75}$.
  - Similar results when instrument uses alternative functional forms

Outline

Main IV Results (1975-2015)

	Δ ln Pop	Δ ln Blt Area	Δ ln Urb Area	Δ ln Pop Dns
	Panel A: All Countries (Observations = 12,849)			
Δ ln(Heights+1)	0.12***	-0.17***	-0.15**	0.27***
	[0.03]	[0.04]	[0.06]	[0.07]
First Stage F	28.42	28.42	28.42	28.42
	Panel B: Developing Economies (Observations = 11,257)			
Δ ln(Heights+1)	0.13***	-0.16***	-0.18**	0.31***
	[0.03]	[0.04]	[0.08]	[0.08]
First Stage F	22.84	22.84	22.84	22.84

- Doubling heights increases city pop by 12%, decreases city built area by 17% (urban area: 15%), increases city pop density by 27% (relative).
- Driven by cities in developing countries (88% of sample)
- Radiance calibrated lights (not top-coded) 1990-2015: 15% (not shown)

Robustness Checks for g(Bedrock Depth, Pop 1975) IVs

- **Identifying assumption:** IVs uncorrelated with city level tall building demand growth conditional on f_1(bedrock), f_2(pop 1975), FE
- Id threat: Correlated with other activities, infrastructure, amenities

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- Id threat: Correlated with other activities, infrastructure, amenities
- **Results hold:** if we restrict the sample to cities with a mean bedrock depth deeper than the 25th pctile in the data (6 m $\approx$ 20 feet):
  - Topsoil up to 0.25 m; Subsoil up to 0.9 m; Root systems up to 2 m
  - Utility lines typically buried max 1-2 m deep
  - Subgrade (formation level) underneath highways never as deep
  - Sometimes deep subway stations (e.g., underground bunkers) $\rightarrow$ drop

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- **Results hold** with controls for $\ln \text{Pop}_{ac75}$ $\times$ (coast, lakes, altitude, ruggedness, ag. suit., temperatures, market access, subways, mines)

Other Robustness Checks

- OLS-IV differences primarily due to measurement error (heights bottom-coded):
  - OLS more muted: 0.05 for pop (IV 0.12), -0.09 for built area (-0.17)
  - Unobserved demand shocks positively correlated with height growth would lead to upward biases in **both** the pop *and* area regressions
  - One-third of IV-OLS gap closed in sample of countries with high Gini of bedrock (LATE)

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  - One-third of IV-OLS gap closed in sample of countries with high Gini of bedrock (LATE)
- Specification checks:
  - Distance to bliss point of bedrock depth instead of quadratic form
  - IV with g(bedrock, ln Pop 1975) in $y = \Delta$ ln Pop 1990-2015 eqn
  - 100 m cut-off to define tall buildings
  - Bedrock depth (BD): 1x1 km. 80% between-pixel BD variation from across cities. Results only slightly stronger with central BD IVs.
  - Conley SE (200 km or 400 km) or admin 1 SE (e.g., states)

Interpretation: Urban Growth vs. Redistribution

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- Estimates driven by developing economies where "clean slate" as of 1975 and context of rural-to-urban (not city-to-city) migration
- Similar estimates if developed economies before 1975 when similar context of rural-to-urban (not city-to-city) migration [BELOW]

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- Using sample of countries $<$20% urbanized in 1975, pop estimate unchanged, built area estimate -0.08 (not significantly different)

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- Using sample of countries <20% urbanized in 1975, pop estimate unchanged, built area estimate -0.08 (not significantly different)
- Additionally control for (similarly instrumented) Δ ln Market Potential in Δ Heights of other cities (inverse Euclidean distance weights)

Heterogeneity (IV) Analysis

Split sample by ...

- Country income and region of the world
- Fraction of 2015 tall building heights that are in residential buildings

  More residential towers countries (Brazil, India, S Korea $\approx$ 90%)

  More office towers countries (Egypt, Pakistan and U.S. $\approx$ 50%)

  Captures preferences and land-use regulations for residential towers
- By initial city size and focusing on developing economies

  Estimate locally weighted IV regressions using a Gaussian kernel in 1975 ln city population for "Asia w/o MENA" and "others"

Heterogeneity in Estimates by Region (1975-2015)

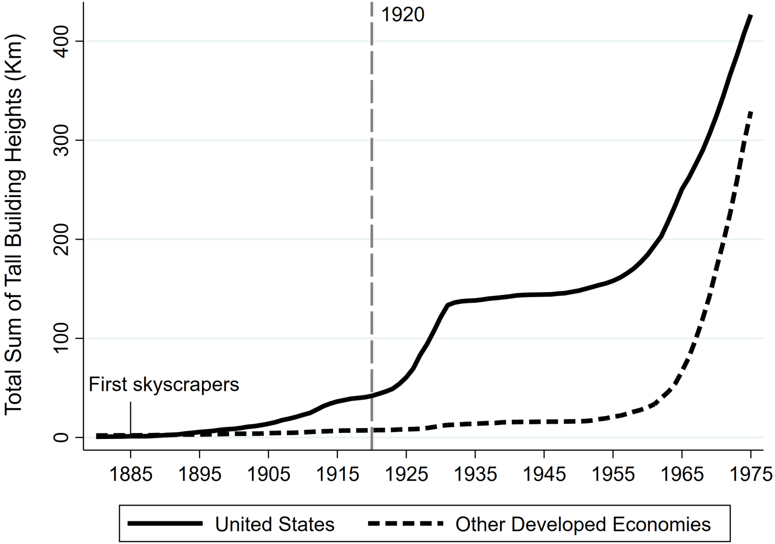
	Developing			Developed		
	Asia xME	Others	Uncons.	Total	USA+Can	Others
	Panel A: Δ ln Population					
Δ ln(Heights+1)	0.17***	0.15**	0.21***	0.00	0.30**	0.01
	[0.03]	[0.07]	[0.04]	[0.03]	[0.12]	[0.02]
	Panel B: Δ ln Built Area					
Δ ln(Heights+1)	-0.20***	-0.26***	-0.39***	-0.04	-0.67*	-0.03
	[0.04]	[0.09]	[0.09]	[0.03]	[0.35]	[0.02]
First Stage F	20.92	7.88	11.36	14.28	5.77	13.68
Observations	6,990	4,267	5,315	1,592	372	1,220

Effects primarily driven by cities in developing economies (88% of cities)

Strong effects in USA-CAN. Nil effects in other developed economies due to central planning in Eastern Europe (and weak IV F-stat in Western Europe and Asia)

→ We focus most of our policy analysis on developing economies.

The Skyscraper Revolution in the Developed World



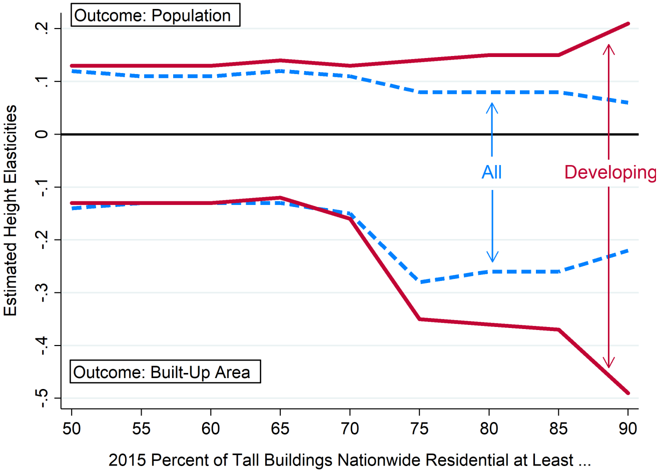
Includes all buildings ≥ 55 meters, ≈ 14 floors. US: Focus on 1920-1975 period.

Historical Evidence for Developed Economies (...-1975)

Countries:	55 Developed		39 Euro	USA	USA	USA
Initial Year:	1850	1900	1850	1920	1920	1920
Δ ln(Heights+1)	0.14**	0.22***	0.20**	0.21	0.21	$0.21^{\dagger}$
	[0.06]	[0.07]	[0.10]	[0.17]	[0.15]	[0.13]
First Stage F	10.94	8.44	5.51	4.05	4.82	7.66
Observations	918	918	1,095	324	324	323
Init Yr Ctrl	N	N	N	N	Y	Y
Drop Las Vegas	N	N	N	N	N	Y

- Analogous IVs based on g(bedrock, ln city population) in the initial year)
- Population elasticities similar to those for developing economies 1975-2015

Results by Country Tall Building Residential Share



Developing economies with higher residential shares in tall buildings (on the right) have greater population *and* land savings responses to height.

Strong response for area (vertical housing and suburbs clear substitutes)

Implied Impacts of 1975-2015 Construction

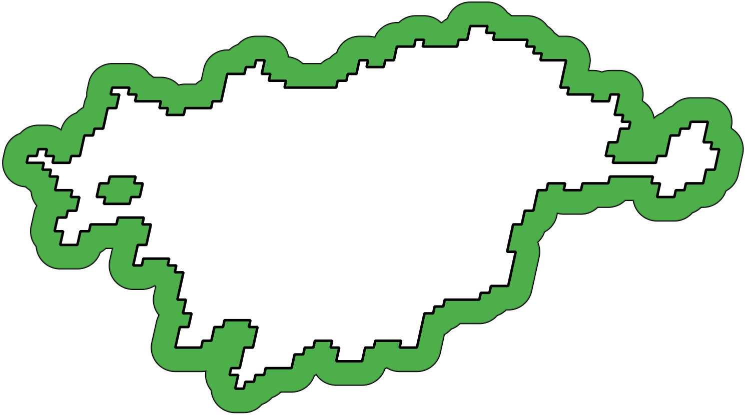
City Pop. 000s (2015)	Number of Cities	1975-2015 ΔHeight km	Share of Height Δ	% of Pop Accomm.	% Area Saved Built	Total
			Panel A: Asian Cities, except Middle East			
0-500	6,514	59	0.02	2	2	1
500-1,000	268	76	0.03	10	9	8
1,000-2,000	114	192	0.07	21	18	15
2,000-5,000	61	527	0.18	47	33	29
5,000+	38	2,001	0.70	58	37	31
All	6,995	2,855	_	23	17	12
			Panel B: Cities in Other Developing Regions			
0-500	3,969	68	0.05	4	5	3
500-1,000	164	123	0.09	20	21	18
1,000-2,000	75	205	0.16	28	28	20
2,000-5,000	54	410	0.31	32	32	24
5,000+	16	501	0.38	38	38	29
All	4,278	1,307	_	18	21	13

Absent construction, 1975-2015 aggregate urban pop change would be ∼20% smaller and aggregate built area change would be ∼20% larger in developing economies

Land Savings Outside 2015 Urbanized Boundaries

We investigate whether land-use outside is tree canopy or vegetation

- Use height elasticity of area by city size to predict land expansion
- Assume spatially uniform land expansion



Prediction for São Paulo (had the city not built tall buildings)

Source of Implied Land Savings

City Pop. 000s (2015)	Number of Cities	% Area Saved Built	% Area Saved Total	% Tree Cover	% Other Veg.	% Non Veg.
			Panel A: Asian Cities, except Middle East			
0-500	6,514	2	1	11	77	12
500-1,000	268	9	8	9	75	16
1,000-2,000	114	18	15	10	72	18
2,000-5,000	61	33	29	9	74	17
5,000+	38	37	31	10	76	14
All	6,995	17	12	10	75	15
			Panel B: Cities in Other Developing Regions			
0-500	3,969	5	3	16	76	8
500-1,000	164	21	18	17	74	10
1,000-2,000	75	28	20	17	70	14
2,000-5,000	54	32	24	15	71	13
5,000+	16	38	29	16	59	26
All	4,278	21	13	16	68	16

∼10-15% from tree cover, ∼70-75% other veg. (incl. cropland), ∼15% non-veg. (desert)

Calculation of "Height Gaps"

Calculate % gap for each city from the aggregate heights justified by fundamentals:

Predict ln sum of heights with lights, population X (national GDP, earthquake risk, ruggedness, elevation, MBD, year FE) using panel data 1995-2020 (R^2=0.64)

Assume 95^{th} pctile of actual log height in each moving window of 100 cities, ordering by predicted heights, is unconstrained.

Resulting height gap for city *ac* is:

$$Gap_{ac} = \max\left(1 - \frac{Heights_{ac2015}}{H^{95}(\widehat{LHEIGHTS}_{ac2015})}, 0\right)$$

Avg in developed: Europe 85%, North America 77%, Asia 64%

Avg in developing: Asia 41%, Africa 48%, LAC 63%

Calculation of Unconstrained Elasticities

Take first step regression in height gap calculation for 2015

Aggregate residuals with city population weights to the country level

Only keep cities with positive country residuals (excluding former communist countries and developed economies) $\rightarrow$ 5,315 cities in 38 countries

Population elasticity of 0.21 and built area elasticity of -0.39

Used to fit the model below

Outline

Taking stock

- Empirics show that supply of height
  - Increases city population
  - Shrinks city area
- Canonical models
  - Population fixed in standard monocentric city model (Alonso, 1964)
  - City area fixed endowment in QSM (Ahlfeldt et al. 2015)
  - City area *grows* in open-city model (Ahlfeldt & Barr, 2022)
- **Need an imperfectly open-city model**
  - Blend standard land-use model (Duranton & Puga, 2015) and QSM
  - Stylized monocentric city structure with endogenous CBD
  - Designed for quantitative analysis

Monocentric City Model with Endogenous CBD

- Highlights causal mechanisms and facilitates evaluation of the welfare consequences of different planning regimes and technological change.
- **Residents:** preferences over floorspace and an outside good; amenity depends on vertical distance (views) and horizontal distance (commuting);

Monocentric City Model with Endogenous CBD

- Highlights causal mechanisms and facilitates evaluation of the welfare consequences of different planning regimes and technological change.
- **Residents:** preferences over floorspace and an outside good; amenity depends on vertical distance (views) and horizontal distance (commuting); migration elasticity to the (representative) city.
  - Rural hinterland. Workers have discrete choice of entering city (Ahlfeldt et al (2022)'s approach to modelling labour market entry)
  - *Imperfectly open* city which nests *closed-city* and *open-city* cases

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  - Rural hinterland. Workers have discrete choice of entering city (Ahlfeldt et al (2022)'s approach to modelling labour market entry)
  - *Imperfectly open* city which nests *closed-city* and *open-city* cases
- **Construction:** zero profits; marginal cost increasing in building height
- **Production:** uses labor and floorspace (offices) as inputs; sector also benefits from views (prod. signalling) and agglomeration economies
- **Equilibrium:** land market clears (highest bidder); labor market clears

Residents

The utility of worker ν:

$$U^o(\nu) = U^o \exp(a^o(\nu))$$

where $o \in \{inside, outside\}$ and $\exp(a^o(\nu))$ is a taste shock

Outside option (hinterland):

$$U^{o=outside} = \widetilde{U}$$

Inside option (representative city):

$$U^{o=inside} = U(x,s) = A^R(x,s)\left(\frac{g}{\alpha^R}\right)^{\alpha^R}\left(\frac{f^R(x,s)}{1-\alpha^R}\right)^{1-\alpha^R},$$

which depends on amenities

$$A^R(x,s) = \bar{a}^R e^{-(\tau^R \times \max(0, x-\underline{x}^R))} s^{\tilde{\omega}^R}$$

Residential Floorspace Bid-Rents

Residents are indifferent across all (x, s) in the city, implying bid-rents

For each location-height:

$$p^R(x,s) = A^R(x,s)^{\frac{1}{1-\alpha^R}} \left(y^R\right)^{\frac{1}{1-\alpha^R}} \bar{U}^{-\frac{1}{1-\alpha^R}}.$$

Averaging across floors puts this in terms of equilibrium height at each location x

$$\bar{p}^R(x) = \frac{1}{S^R(x)} \int_0^{S^R} p^R(x,s)ds = \frac{a^R(x)}{1+\omega^R} S^R(x)^{\omega^R},$$

where

$$a^R(x) = \tilde{A}^R(x)^{\frac{1}{1-\alpha^R}} \left(y^R\right)^{\frac{1}{1-\alpha^R}} \bar{U}^{-\frac{1}{1-\alpha^R}}$$

Production

Firms use labor and floorspace to produce:

$$g(x,s) = A^C(x,s)\left(\frac{l}{\alpha^C}\right)^{\alpha^C}\left(\frac{f^C(x,s)}{1-\alpha^C}\right)^{1-\alpha^C}$$

and (agglomeration economies and production amenity decay)

$$A^C(x,s) = \bar{a}^C N^{\beta} e^{-(\tau^C \times \max(0, x-\underline{x}^C))} s^{\tilde{\omega}^C}$$

Leading to horizontal commercial bid-rents

$$\bar{p}^C(x) = \frac{1}{S^C(x)}\int_0^{S^C} p^C(x,s)ds = \frac{a^C(x)}{1+\omega^C} S^C(x)^{\omega^C},$$

where

$$a^C(x) = \tilde{A}^C(x)^{\frac{1}{1-\alpha^C}} (y^C)^{\frac{\alpha^C}{\alpha^C-1}}$$

Construction (Again)

Same as before, but separately by Residential (R) or Commercial (C) sector U: We allow production function parameters to differ by sector

Subbing in bid-rents from above,

$$S^{*U}(x) = \Big(\frac{a^U(x)}{c^U(1+\theta^U)}\Big)^{\frac{1}{\theta^U-\omega^U}}$$

Under perfect competition (0 profits), the use-specific equilibrium

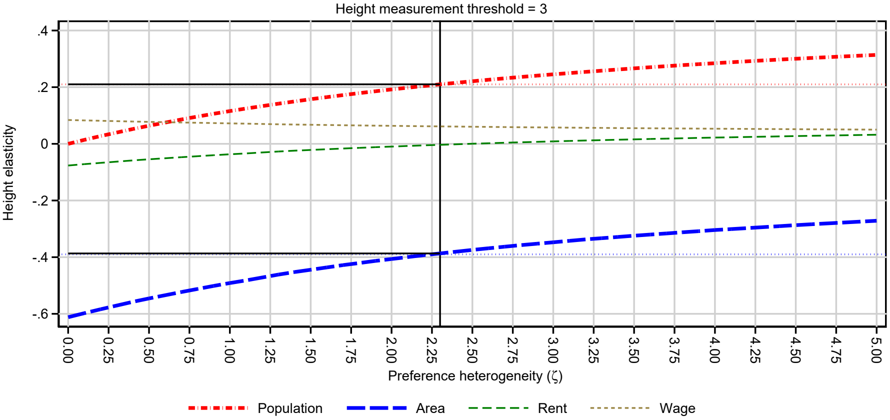
bid-rents for land are

$$r^U(x) = \frac{a^U}{1+\omega^U}\big(\tilde{S}^U\big)^{1+\omega^U} - c^U\big(\tilde{S}^U\big)^{1+\theta^U}$$

which goes to the highest bid use in equilibrium

	Parameter	Value
$1-\alpha^C$	Share of floor space at inputs	0.15
$1-\alpha^R$	Share of floor space at consumption	0.33
β	Agglomeration elasticity of production amenity	0.03
θ^C	Commercial height elasticity of construction cost	0.5
θ^R	Residential height elasticity of construction cost	0.55
ω^C	Commercial height elasticity of rent	0.03
ω^R	Residential height elasticity of rent	0.07
τ^C	Production amenity decay	0.014
τ^R	Residential amenity decay	0.016
ζ	Preference heterogeneity	2.3

- Set amenity decay values to match average height gradients in data: CoreLogic for Chicago, patterns verified for the world using satellite-based building volumes for unconstrained 1m+ cities (Esch et al 2023)
- Set preference heterogeneity to 2.3 to match height elasticity estimates
  - Pop.-height elasticity = 0.22; Area-height elasticity = -0.38 SMM
  - From countries with many cities *unconstrained* by height regulation (conditional height gaps estimated globally by Barr & Jedwab 2023 (REE))



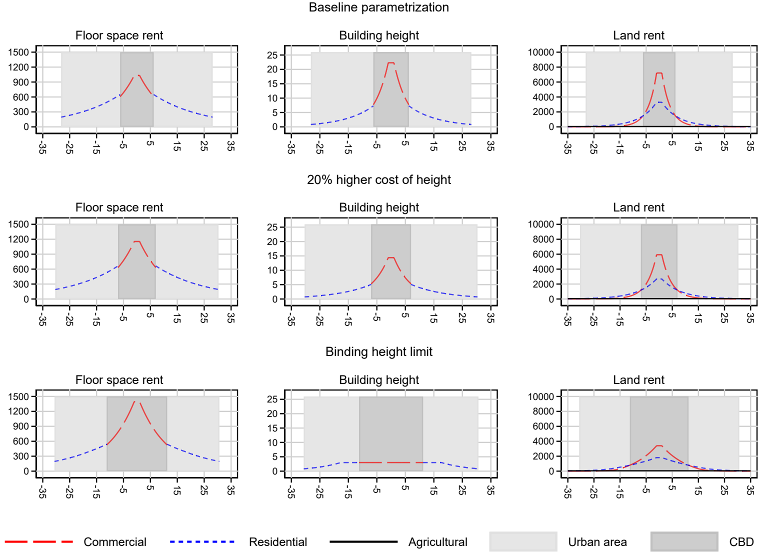
The larger ζ, the stronger the pop and area responses to heights

$\Rightarrow$ Also calibrate height measurement threshold ($\mathcal{T}$) in model

$\Rightarrow$ Height threshold less consequential, but must be positive

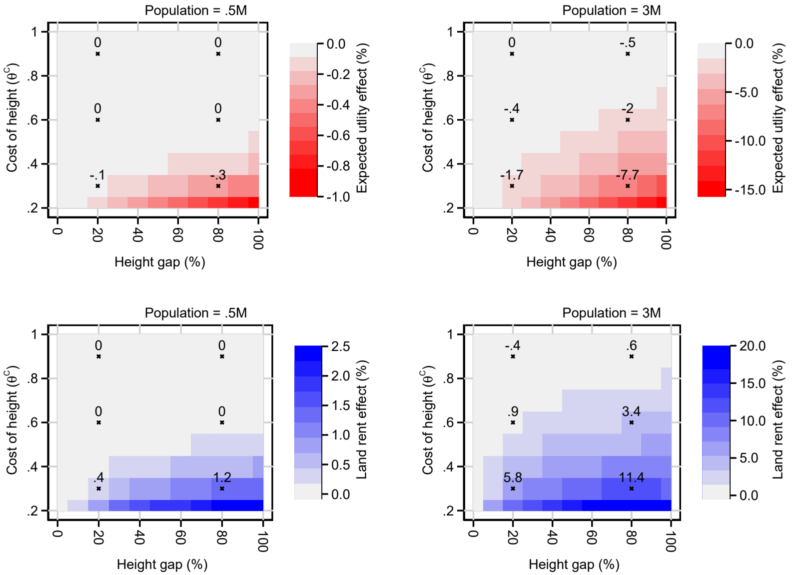
$\Rightarrow$ Under $\zeta = 2.3, \mathcal{T} = 3$, we exactly match moments in data

Objective Function



Increasing cost of height and height limits reduce expected utility

⇒ Wage (-3/-8%), commuting cost (+3/+8%), population (-10/-15 %), urban area (+16/+13%), commercial rent (+3/+6%), residential rent (+1/-15%)



Worker utility decreases and land rent increases in city pop size (more demand for heights) when height restriction *and* lower city-specific cost of height:

→ Height restriction more consequential if lower cost of height (good bedrock)

Global worker welfare effects

- Calibrate model and conduct counterfactuals for the 12,877 world cities
  - Map bedrock to cost of height, invert $\{\bar{S}^U, \tilde{U}\}$ to match height gap, pop

World region	Urban pop. (BN)	City characteristics In cities >1 mill.	Cost of height θ	Est. height gap	Expected utility ($\mathcal{V}$) No tall building	Actual height limit
Mean, Developing (G)	2.87	43.3%	0.54	44.8%	–4.2%	–3.1%
Europe, D	0.25	41.4%	0.32	84.6%	–5.8%	–4.9%
North America, D	0.17	67.3%	0.43	76.6%	–8.3%	–6.3%
Mean, Developed (D)	0.64	59.6%	0.39	75.9%	–7.7%	–5.9%
Mean, All (G & D)	3.51	46.3%	0.51	50.5%	–4.8%	–3.6%

- Tall buildings have the potential to increase worker welfare by **4.8%**

  Larger in developed economies (large cities*low cost of height*large gap)

  Larger in North America (large cities >> cost of height or gap)
- **3.6%** still to be realized (likely due to height restrictions)

Global worker welfare effects

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  - Map bedrock to cost of height, invert $\{\bar{S}^U, \tilde{U}\}$ to match height gap, pop

World region	Urban pop. (BN)	City characteristics: In cities >1 mill.	City characteristics: Cost of height θ	City characteristics: Est. height gap	Agg. land rent ($\mathcal{R}$): No tall building	Agg. land rent ($\mathcal{R}$): Actual height limit
Mean, Developing (G)	2.87	43.3%	0.54	44.8%	5.3%	4.7%
Europe, D	0.25	41.4%	0.32	84.6%	7.4%	8.3%
North America, D	0.17	67.3%	0.43	76.6%	10.0%	10.4%
Mean, Developed (D)	0.64	59.6%	0.39	75.9%	9.5%	9.5%
Mean, All (G & D)	3.51	46.3%	0.51	50.5%	6.1%	5.6%

- Tall buildings have the potential to reduce land rent by **6.1%**
- Aggregate land rent would fall by **5.6%** if height limits removed

  Improving tall building construction and removing height restrictions lead to transfers from the immobile land factor to the mobile labor force.

Conclusions

- The Skyscraper Revolution has fundamentally changed the nature of cities around the world, especially in developing economies.
- Estimated elasticities of city population of 0.12, built up area of -0.17 and city population density of 0.29 with respect to city height.

Conclusions

- The Skyscraper Revolution has fundamentally changed the nature of cities around the world, especially in developing economies.
- Estimated elasticities of city population of 0.12, built up area of -0.17 and city population density of 0.29 with respect to city height.
- Implication is that skyscraper construction has accommodated a large share of urbanization and facilitated large land savings globally.
- Land savings largest for short vegetation/cropland, then forested land
- Calibrated model indicates total potential welfare gain of about 4%, of which about only one-fourth has been realized.

    Welfare cost will increase over time as cost of height falls (in our construction costs data, the cost of height decreased by $\approx$2% per year)

Appendix

For each combination of $\{\theta, \zeta, \mathcal{T}\}$, we solve the model and compute the endogenous outcomes city area

$$\mathcal{L}_{\theta}^{\zeta,\mathcal{T}} = \int_0^{(x_1)^{\theta,\zeta,\mathcal{T}}} \mathcal{L}(x) dx,$$

city population

$$N_{\theta}^{\zeta,\mathcal{T}} = \int_{(x_0)^{\theta,\zeta,\mathcal{T}}}^{(x_1)^{\theta,\zeta,\mathcal{T}}} (n(x))^{\theta,\zeta} dx,$$

and city tall building height

$$H_{\theta}^{\zeta,\mathcal{T}} = \int_0^{(x_1)^{\theta,\zeta,\mathcal{T}}} \mathcal{L}(x) \left((S^C(x))^{\theta,\zeta} - \mathcal{T} \right) dx + \int_{(x_0)^{\theta,\zeta,\mathcal{T}}}^{(x_1)^{\theta,\zeta,\mathcal{T}}} \mathcal{L}(x) \left((S^R(x))^{\theta,\zeta} - \mathcal{T} \right) dx.$$

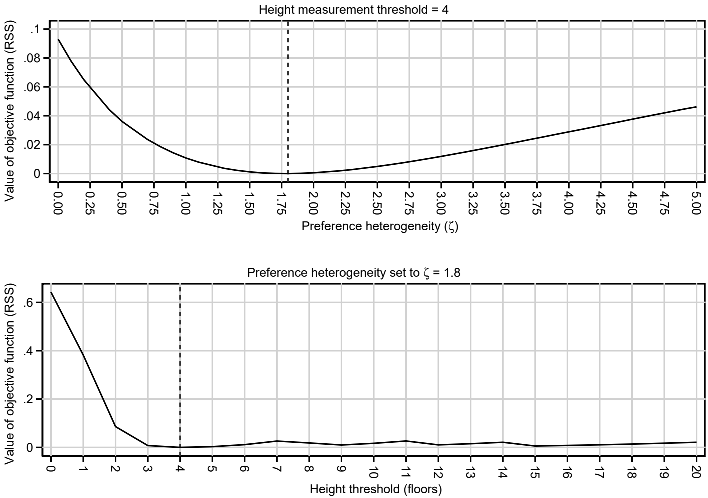
For each combination of $\{\zeta, \mathcal{T}\}$, we run the following regressions on the model-based outcomes to recover our moments in the model $\{\tilde{\beta}^N, \tilde{\beta}^{\mathcal{L}}\}$:

$$\ln \mathcal{L}_\theta^{\zeta,\mathcal{T}} = c^{\mathcal{L},\zeta,\mathcal{T}} + \tilde{\beta}^{\mathcal{L}}_{\zeta,\mathcal{T}} \ln H_\theta^{\zeta,\mathcal{T}} + \tilde{\epsilon}_\theta^{\mathcal{L},\zeta,\mathcal{T}}$$
$$\ln N_\theta^{\zeta,\mathcal{T}} = c^{N,\zeta,\mathcal{T}} + \tilde{\beta}^{N}_{\zeta,\mathcal{T}} \ln H_\theta^{\zeta,\mathcal{T}} + \tilde{\epsilon}_\theta^{N,\zeta,\mathcal{T}}$$

We find our preferred combination of $\{\zeta, \mathcal{T}\}$ by minimizing the value of the residual sum of squares of the moments in model and data:

$$\zeta, \mathcal{T} = \arg \min_{\zeta \in \mathcal{Z}, \mathcal{T} \in \mathcal{R}} \sum_{o \in N, \mathcal{L}} \left(\hat{\beta}^o - \tilde{\beta}^o\right)^2$$

Height elasticities



Height elasticities