Capital-Embodied Structural Change

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Introduction

- Structural change: reallocation of economic activity across agriculture, manufacturing, and services.
- The study of the process of structural change has focused almost exclusively on sector-specific factor-neutral technical change.
- But factor-augmenting technical change has been shown to account for more than half of overall output growth.

  (Greenwood, et. al. 1997).
- We study sector-specific factor-augmenting technical change → embodied in capital.

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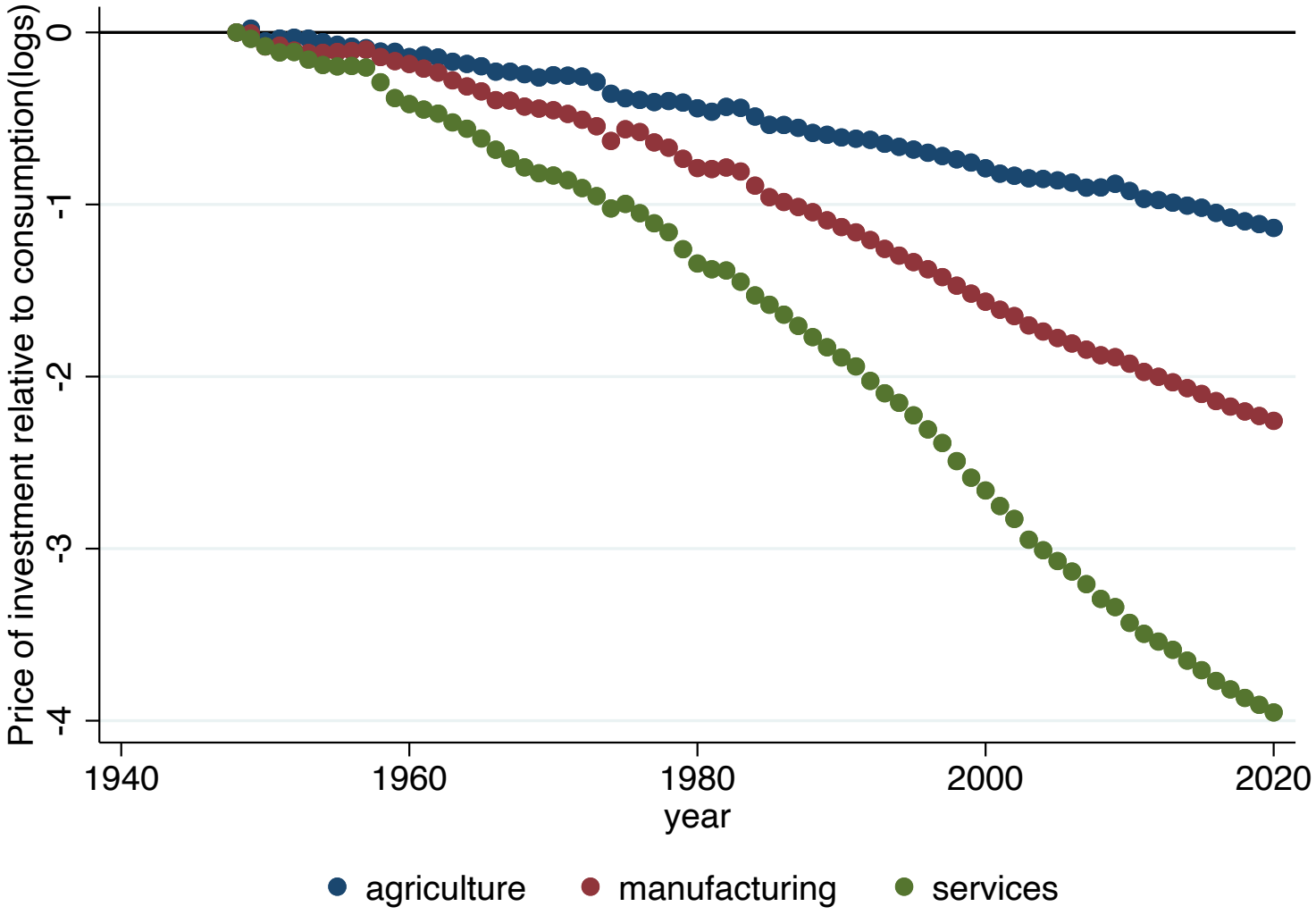

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- Document larger sectoral disparities in CETC than in TFP growth.

  US time-series and multiple cross-sections of countries.

- New multisector model with:
  - Sectorial CETC from multiple investment goods,
  - Endogenous disparities in factor shares.

- Quantify *CETC-induced shift in economic activity across sectors.* → capital-embodied structural change.

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- Quantify *CETC-induced shift in economic activity across sectors.* → capital-embodied structural change.

  37% of the reallocation of labor into services,
  88% of the reallocation of labor out of agriculture.

Contributions

1. *Unpack sectoral TFP growth*: document systematic disparities in investment composition across sectors (and CETC).

2. Highlight *heterogeneity in the type of investment* & *movements in factor shares* with structural change.

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Why do we care?

- Developing countries import most of their equipment.

  Eaton & Kortum (2001), Mutreja et.al. (2018).

- Sectoral productivity paths need not be set in stone.

  Alvarez-Cuadrado and Poschke (2011).

  services holds fastest CETC and slowest TFP growth, *can productivity trends reverse?* → Baumol's disease.

Overview

1. Empirical evidence.
   - Framework to look at the data.
   - Main findings.
2. A model of capital-embodied structural change.
3. The role CETC for structural change.

Empirical Evidence

Overview: minimal framework

- Sectoral goods:

$$
\begin{aligned}
Y_{st} &= A_{st}\,\overbrace{F(K_{st}, N_{st})}^{\text{CRS}}, \\
A_{st+1} &= A_{st}(1 + \gamma_{A_s}),
\end{aligned}
$$

and differ by:

1. **factor-neutral technology**,
2. capital used → **sectoral CETC**.

Sectoral capital

- J equipment goods, investment X_j, of different CETC:

$$\begin{aligned} Y_t &= C_t + \sum_j \chi_{jt}, \\ X_{jt} &= A_{jt}\chi_{jt}. \\ A_{xjt+1} &= (1+\gamma_{A_{xj}})A_{xjt}, \end{aligned}$$

$\Rightarrow \frac{P_{xjt}}{P_{\chi t}} = \frac{1}{A_{xjt}}$.

- Sector-specific investment aggregator with constant returns:

$$K_{st+1} = \mathbf{I}_s(\{X_{jst}\}_j) - \delta_s K_{st},$$

and $X_{jt} = \sum_s X_{jst}$.

Factor-augmenting technical change & structural change

$$\frac{P_{st}}{P_{s't}} = \frac{\overbrace{1-\alpha_{s't}}^{\frac{\partial F_n N}{F}}}{1-\alpha_{st}} \frac{\overbrace{Y_{s't}/N_{s't}}^{\text{labor prod.}}}{Y_{st}/N_{st}}$$

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- Sectoral factor share: $\alpha_{st} = \alpha_s$ (Acemoglu and Guerrieri, 2008)

$$\frac{P_{st}}{P_{s't}} = \frac{A_{s't}}{A_{st}} \frac{F_{s'}\left(\frac{K_{s't}}{N_{s't}}\right)}{F_s\left(\frac{K_{st}}{N_{st}}\right)}, \qquad \frac{K_{st}}{N_{st}} = \frac{W_t}{r_t} \frac{\alpha_s}{1-\alpha_s}.$$

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- Sectoral CETC: $\mathbf{r_{s't}}$

$$\frac{P_{st}}{P_{s't}} = \frac{A_{s't}}{A_{st}} \frac{F_{s'}\left(\frac{K_{s't}}{N_{s't}}\right)}{F_s\left(\frac{K_{st}}{N_{st}}\right)}, \qquad \frac{K_{st}}{N_{st}} = \frac{W_t}{r_{st}} \frac{\alpha_{st}}{1-\alpha_{st}}.$$

Factor-augmenting technical change & structural change

Measurement

$$\gamma_{\frac{P_{st}}{P_{s't}}} \approx \left(\gamma_{\tilde{A}_{s't}} - \gamma_{\tilde{A}_{st}}\right) + \left(\frac{\alpha_{s't}}{1-\alpha_{s't}}\gamma_{r_{s't}} - \frac{\alpha_{st}}{1-\alpha_{st}}\gamma_{r_{st}}\right).$$

$\gamma_{\tilde{A}_{st}} = \gamma_{A_{st}} + (1-\alpha_{st})\gamma_{1-\alpha_{st}} + \alpha_{st}\gamma_{\alpha_{st}}.$

Factor-augmenting technical change & structural change

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$\gamma_{\tilde{A}_{st}} = \gamma_{A_{st}} + (1-\alpha_{st})\gamma_{1-\alpha_{st}} + \alpha_{st}\gamma_{\alpha_{st}}.$

- Long-run dynamics:

$$\gamma_{r_s} = \sum_j \kappa_{js}(\gamma_{P_{xj}} - \gamma_{P_c}) = -\sum_j \kappa_{js}\gamma_{A_{xj}}.$$

where $\kappa_{jst} \equiv \frac{P_{xjt}X_{jst}}{\sum_{j'} P_{xj't}X_{j'st}}$.

- <u>Measurement:</u>

$$\gamma_{\frac{P_{st}}{P_{s't}}} \approx \left(\gamma_{\tilde{A}_{s't}} - \gamma_{\tilde{A}_{st}}\right) + \sum_j \left(\frac{\alpha_{s't}}{1-\alpha_{s't}}\kappa_{js't} - \frac{\alpha_{st}}{1-\alpha_{st}}\kappa_{jst}\right)\gamma_{A_{xjt}}.$$

Evidence for the US: 1948-2020

Data construction

- Price of sectoral output, BEA Herrendorf et.al., 2015.
  3-digit NAICS sectors aggregated to 3 sectors.
- (nominal and chained-weighted) Value added by sector, NIPA.
- Quality-adjusted price of equipment to consumption:
  Cummins & Violante, 2001. DiCecio, 2009.
  22 equipment categories plus 3 categories of software.
  ...aggregated to 3 sectors.
- (nominal) Investment and stocks by equipment and sector, BEA fixed assets tables.

Sector definition

3-sector	NAICS 2-digit
Agriculture	Farms, Forestry and Fishing
Manufacturing	Manufacturing
	Mining
Services	Wholesale Trade
	Retail
	Transportation
	Entertainment
	Acommodation
	Business Administration
	Health Services
	Professional Services
	Education
	Finance and Insurance

No construction (manufacturing) and no real estate (services).

Relative price of investment by sector

- CRS investment aggregator in each sector:

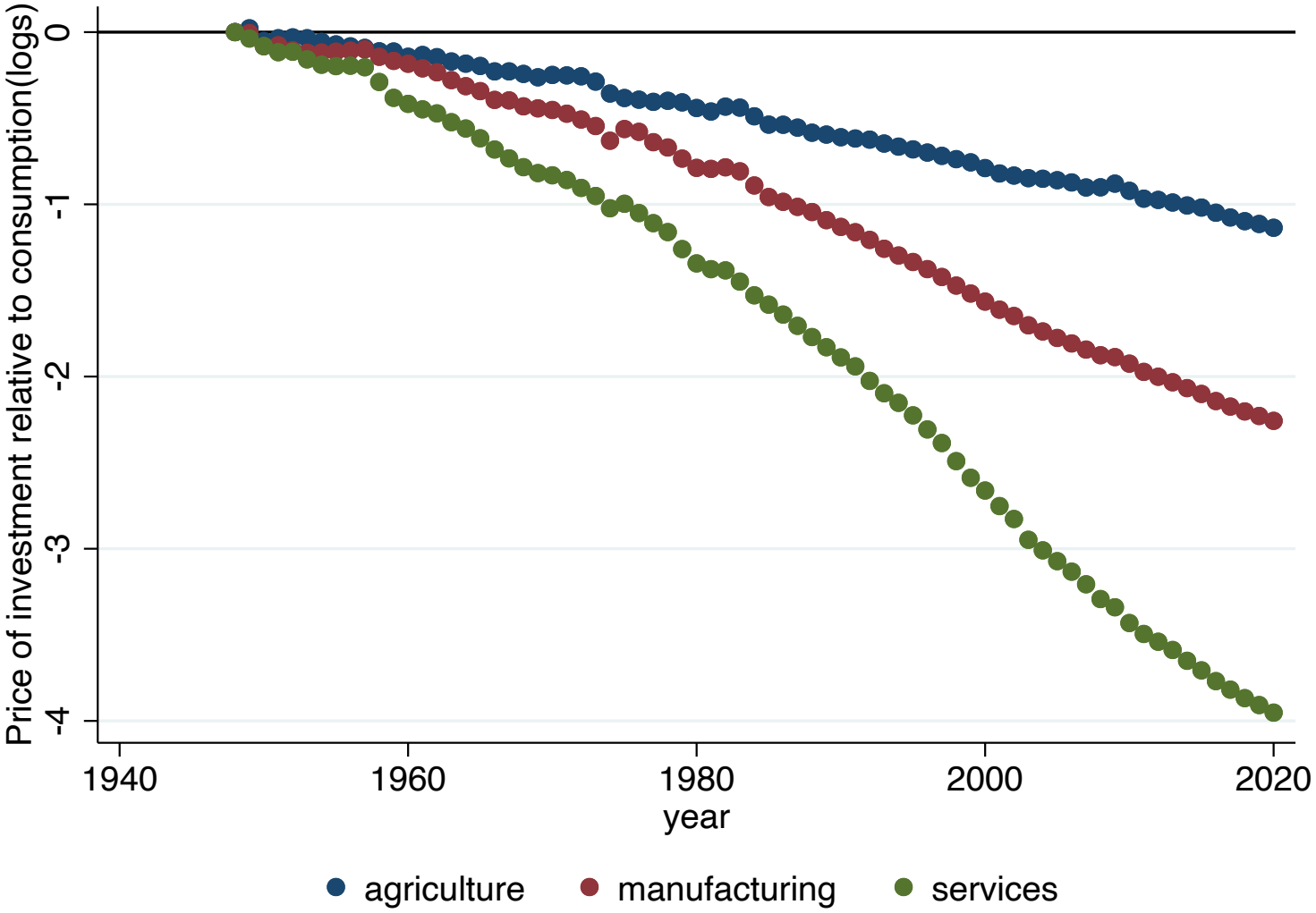
$$\mathbf{I}_s(\{X_{jst}\}_j).$$

- Change in the relative price of investment to consumption:

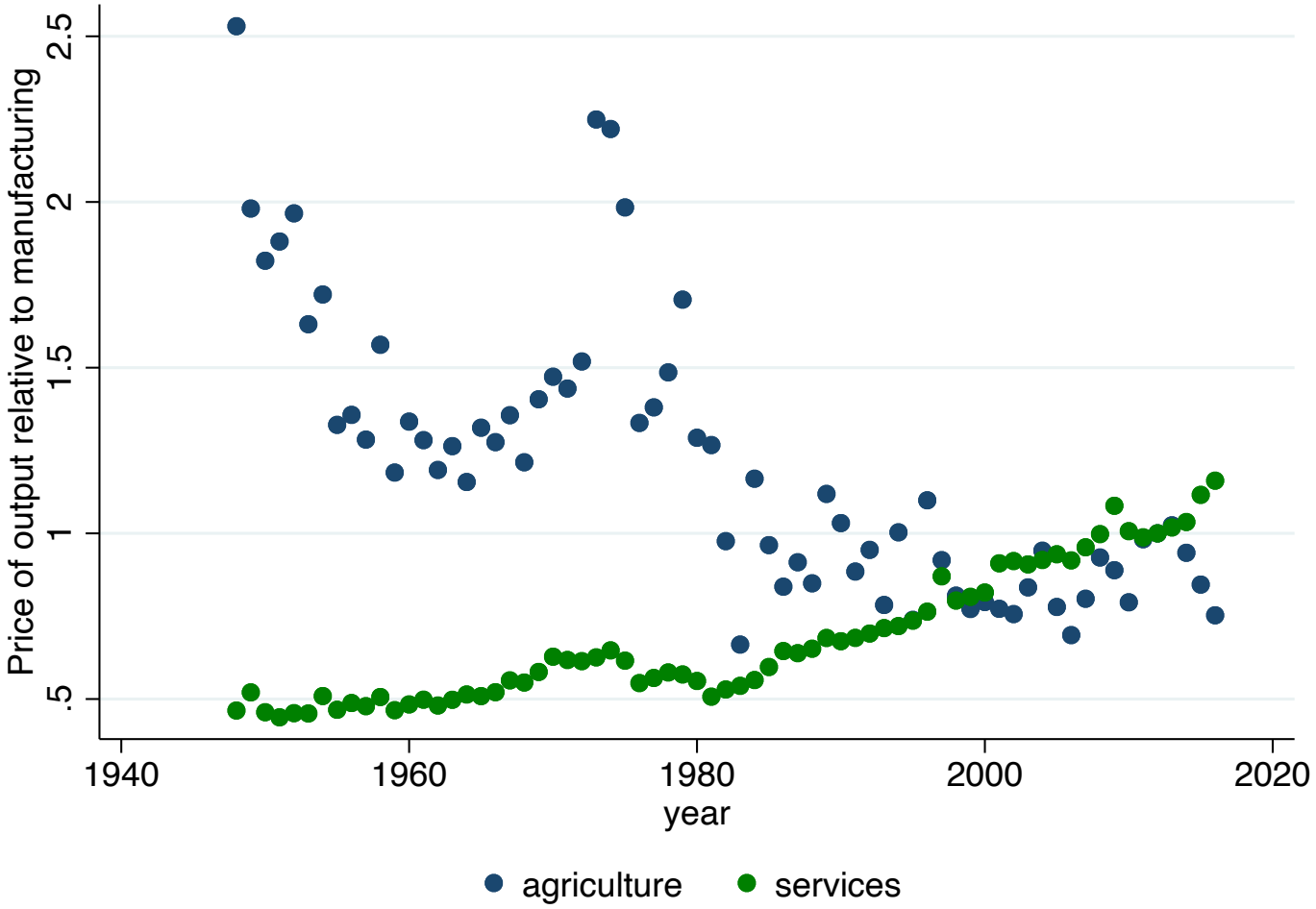
$$d\ln(P_{xst}) = \sum_j \frac{P_{xjt}X_{jst}}{\sum_j P_{xjt}X_{jst}} d\ln(P_{xjt})$$

P_{xjt} is the relative price of investment good j to consumption.
$P_{xjt}X_{jst}$ nominal investment.

CETC by sector

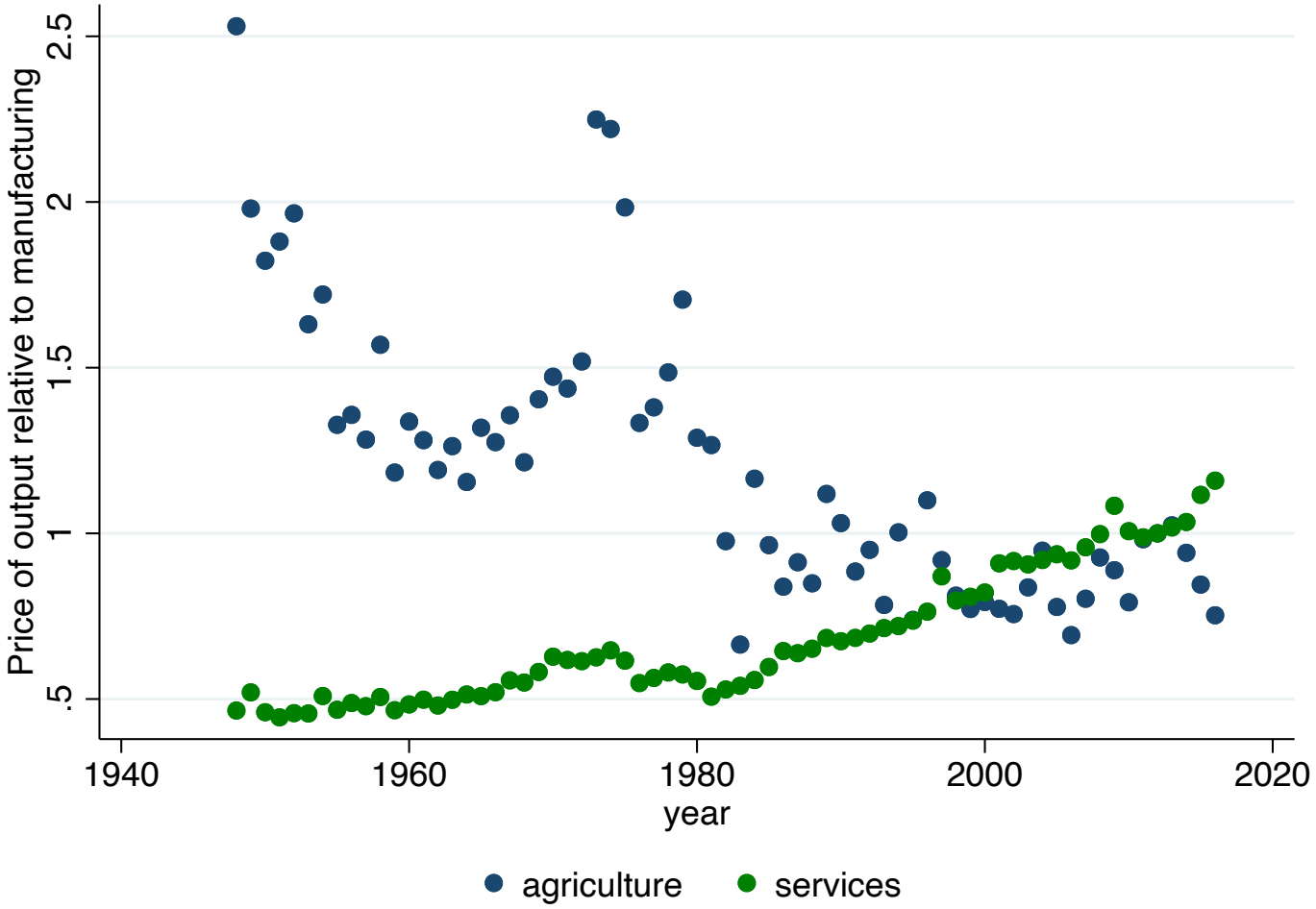


Relative prices by sector, P_s/P_{manuf}



$\gamma \frac{P_s}{P_{s'}}$

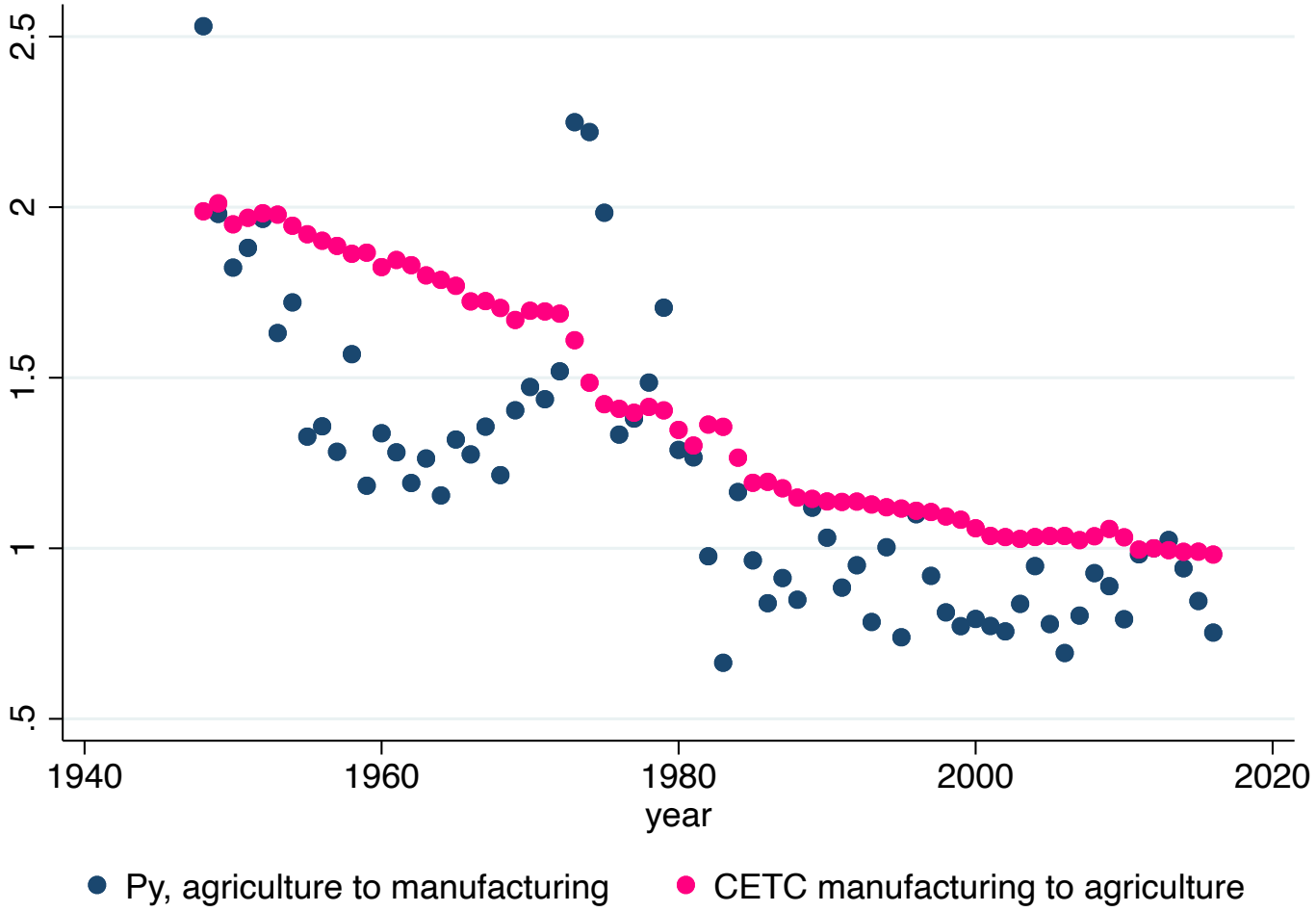
Relative prices by sector, P_s/P_{manuf}



$$\gamma_{\frac{P_s}{P_{s'}}} \approx \left(\gamma_{\tilde{A}_{s'}} - \gamma_{\tilde{A}_s}\right) + \underbrace{\sum_j \left(\frac{\alpha_{s't}}{1-\alpha_{s't}}\kappa_{js't} - \frac{\alpha_{st}}{1-\alpha_{st}}\kappa_{jst}\right)\gamma_{A_{xjt}}}_{\text{CETC}}$$

Relative prices and CETC

Agriculture



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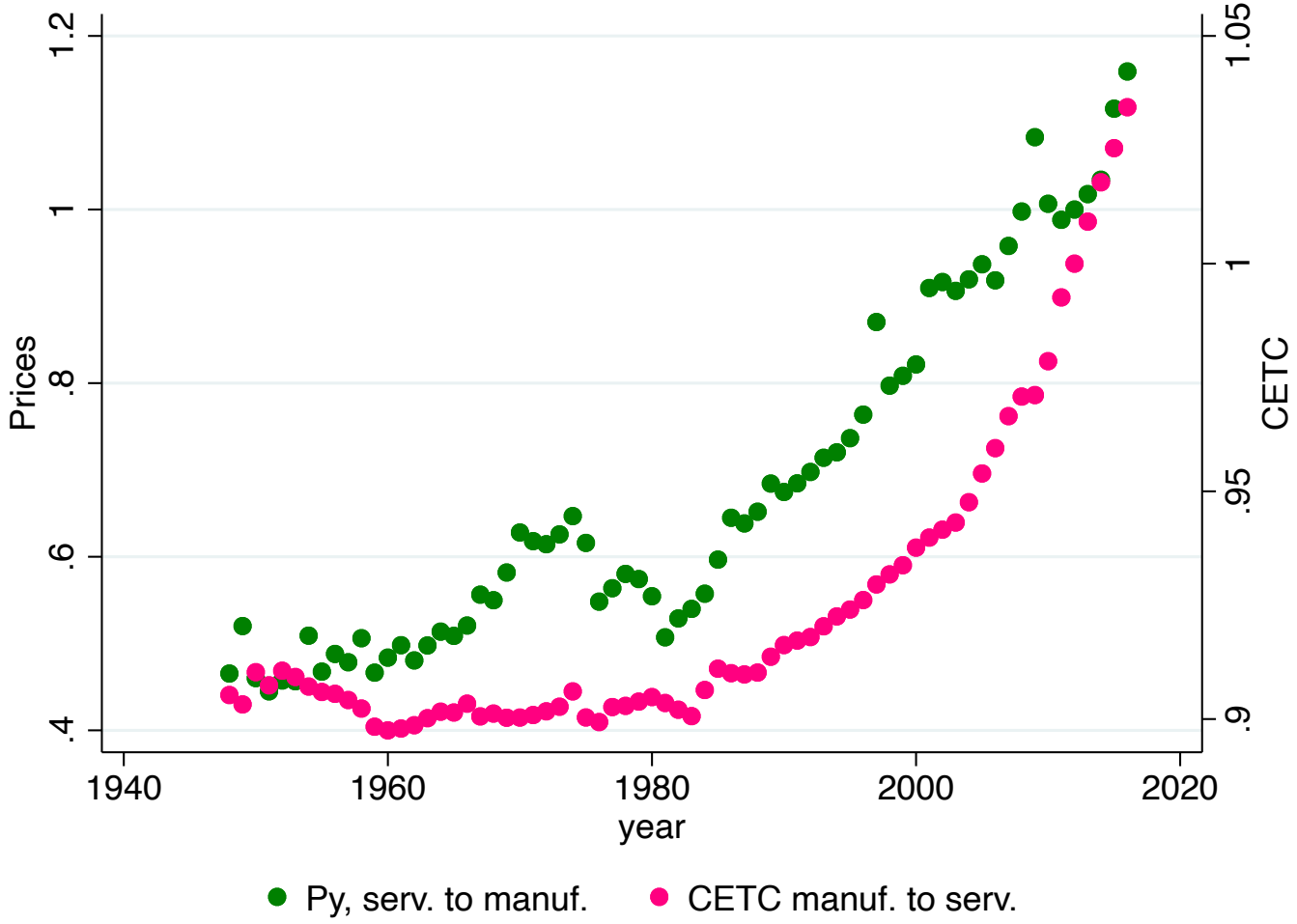
Relative prices and CETC

Services



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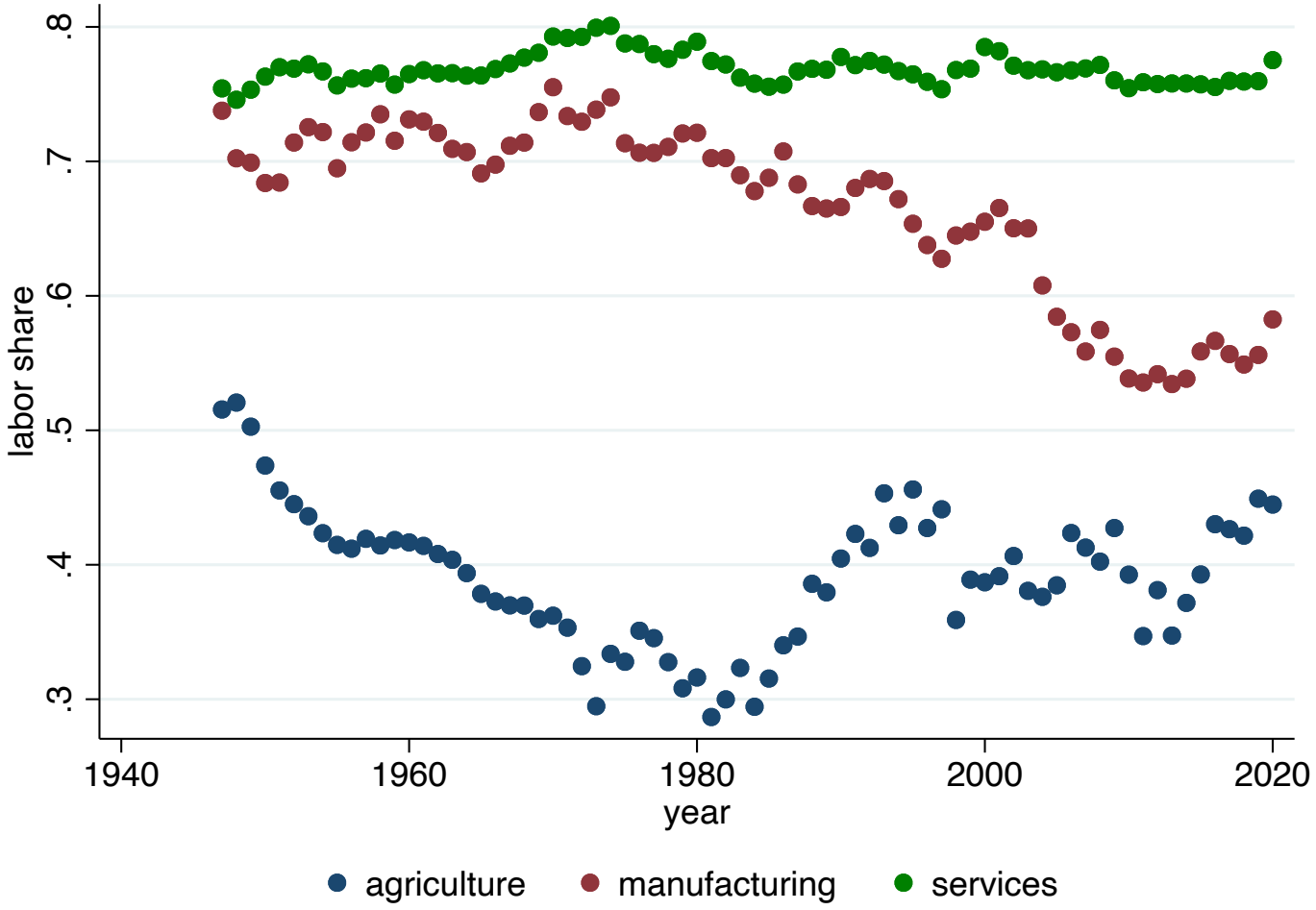
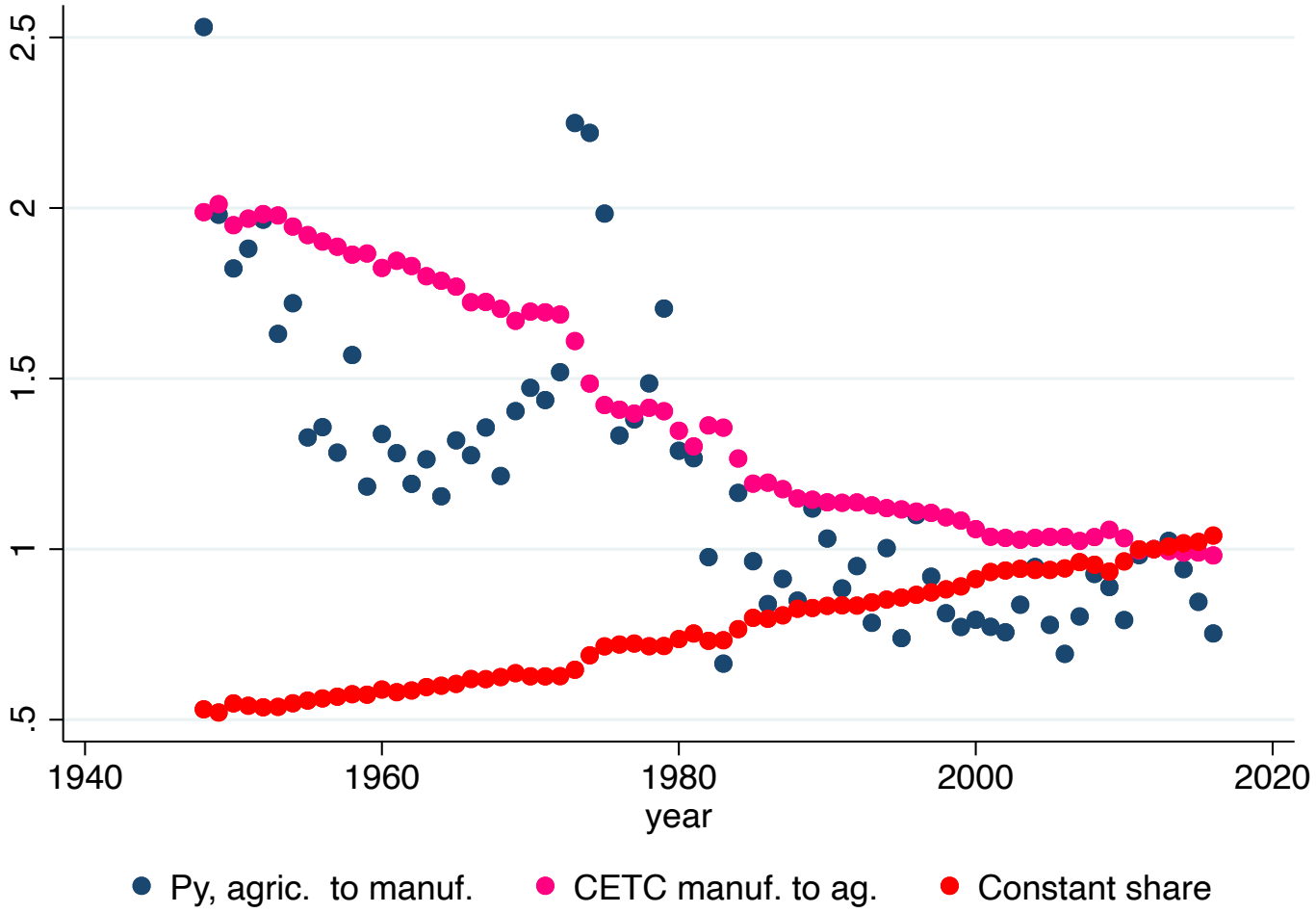
Labor share


.8
.7
.6
.5
.4
.3
labor share
1940
1960
1980
2000
2020
year
agriculture
manufacturing
services

Constant labor share

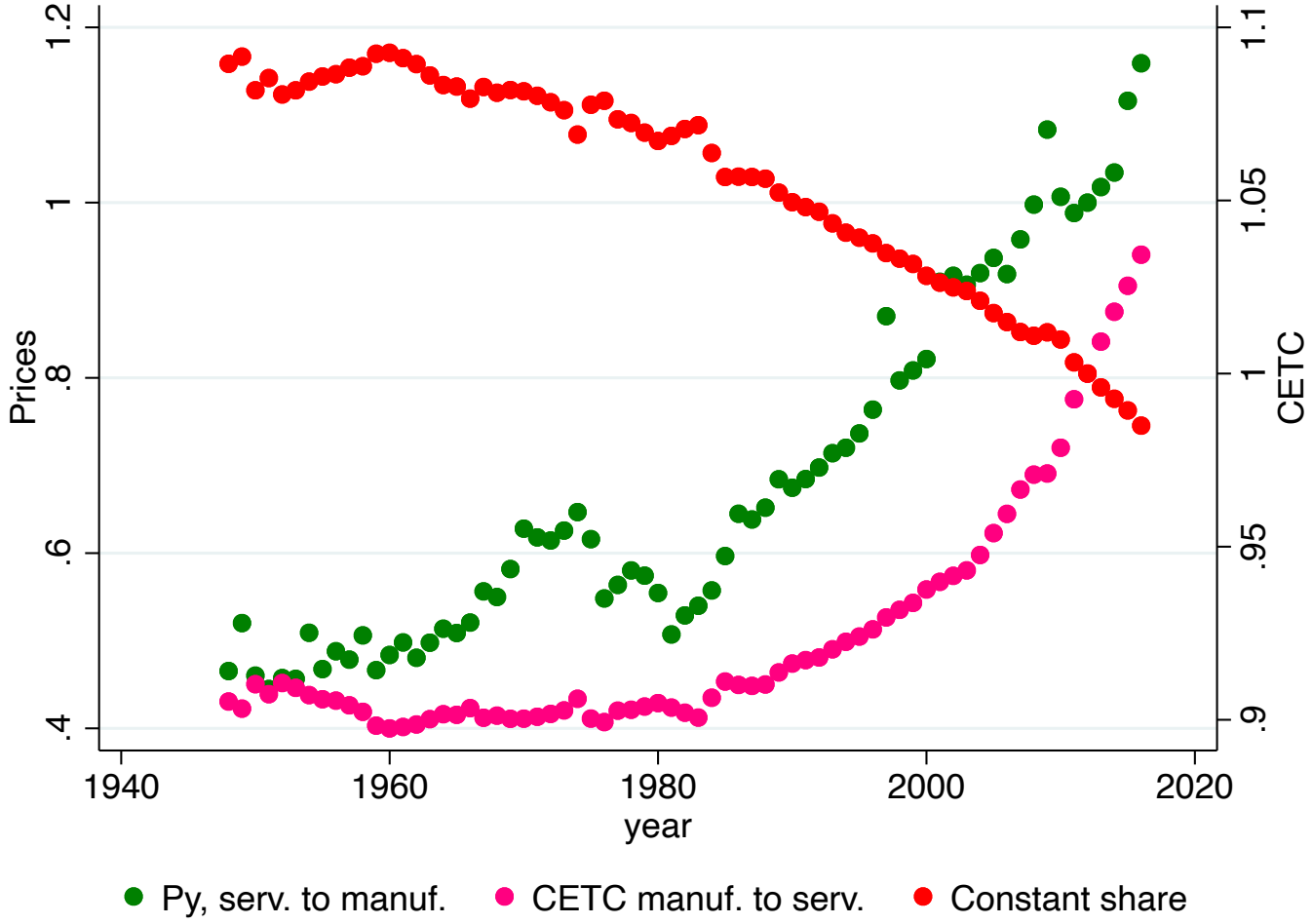
Agriculture



constant share: $1 - \alpha$ set to Herrendorf et.al. (2015).

Constant labor share

Services



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Evidence for the US

Summary

1. Systematic disparities in CETC across sectors.

	Agriculture	Manufacturing	Services
CETC, $\gamma_{A_{xs}}$	1.51	2.56	4.85

2. Non-trivial movements in the labor share within sectors.

3. CETC likely driving the trend in relative price of agriculture and (partially) services to manufacturing.

A model of capital-embodied structural change.

Acemoglu (2003), Jones and Liu (2021) + capital embodied technology.

Sectoral technology

- Production requires completing a measure 1 of activities:

$$Y_{st} = \left[\int_o^1 Q_{ist}^{\rho} di \right]^{\frac{1}{\rho}},$$

for $\rho < 0$.

- Activities can be performed with labor:

$$Q_{ist} = \zeta_{ist}^{\frac{\rho-1}{\rho}} N_{ist} \qquad i \in [0, 1],$$

$\zeta_{ist+1} = \zeta_{ist}(1 + \gamma_{A_s})$.

- Share m_{st} can also be performed with capital:

$$Q_{ist} = K_{ist} \qquad i \in [0, m_{st}],$$

$m_{st+1} = m_{st}(1 + \gamma_{m_s})$.

Optimal allocations

- ζ_{ist} strictly increasing in $i \rightarrow$ threshold for activities performed with capital, m_{st}:

$$r_{st} \leqslant w_t(\zeta_{ist}^{-1})^{\frac{\rho-1}{\rho}}, \qquad \rho < 0.$$

race between labor productivity growth $\uparrow \zeta_{ist}$ *and the user cost of capital* $\downarrow r_{st}$.

- Capital share in the sector:

$$\frac{r_{st}K_{st}}{Y_{st}P_{st}} = m_{st}\left(\frac{r_{st}}{P_{st}}\right)^{\frac{\rho}{\rho-1}}.$$

Optimal allocations: sectoral output

$$Y_{st} = \left[\left((1 - m_{st}) Z_{st}^{-1} \right)^{(1-\rho)} N_{st}^{\rho} + m_{st}^{(1-\rho)} K_{st}^{\rho} \right]^{\frac{1}{\rho}},$$

for $Z_{st}^{-1} = \frac{1}{1-m_{st}} \int_{m_{st}}^{1} \frac{1}{\zeta_{ist}} d(i)$.

- $A_{nst} \equiv Z_{st}^{\frac{\rho-1}{\rho}}$ to index labor productivity.
- A_{xst} to index CETC:

$$K_{st} = A_{xst} \tilde{K}_{st}, \quad A_{xst+1} = A_{xst}(1 + \gamma_{Axs}).$$

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$$K_{st} = A_{xst} \tilde{K}_{st}, \quad A_{xst+1} = A_{xst}(1 + \gamma_{Axs}).$$

$\Rightarrow$ Output can be rewritten as:

$$Y_{st} = \left[(b_{st}^{n} N_{st})^{\rho} + (b_{st}^{k} \tilde{K}_{st})^{\rho} \right]^{\frac{1}{\rho}},$$

for $b_{st}^{n} = \overbrace{((1 - m_{st}))^{\frac{1-\rho}{\rho}} A_{nst}}^{\text{labor-augmenting}}$ and $b_{st}^{k} = \overbrace{m_{st}^{\frac{1-\rho}{\rho}} A_{xst}}^{\text{capital-augmenting}}$.

Observation: when $\rho \to 0$, m_{st} arbitrary, technology Cobb-Douglas.

Asymptotic BGP (despite Uzawa)

- Constant capital share for:

$$\gamma_{m_s} = \frac{\rho}{\rho - 1}(-\gamma_{r_s}) = \frac{\rho}{\rho - 1}\gamma_{A_{xs}},$$

→ "Mechanization" is slower than CETC:

$$\gamma_{m_s} < \gamma_{A_{xs}}, \quad \text{for} \quad \rho < 0.$$

→ Technical change is labor-augmenting (long-run).

constant $b^k_{st} = m_{st}^{\frac{1-\rho}{\rho}} A_{xst}$ for log-preferences in consumption.

- Constant rate of convergence to the BGP for constant $\gamma_{b^n_s}$:

$$\gamma_Y \approx (\rho - 1)\gamma_{b^n_s} = \frac{\rho - 1}{\rho}(-\gamma_{1-m_s} + \gamma_{Z_s}),$$

→ γ_{1-m_s} is constant,
→ γ_{m_s} is monotonically decreasing and so is $\gamma_{A_{xs}}$.

Along the transition: identification

- "Mechanized" activities → labor shares, CETC:

$$1 - \frac{r_{st}K_t}{P_{st}Y_{st}} = 1 - \alpha_{st} \quad = 1 - m_{st}\left(\frac{r_{st}}{P_{st}}\right)^{\frac{\rho}{\rho-1}}.$$

- Labor augmenting → employment, output, labor shares:

$$\frac{w_t L_{st}}{P_{st}Y_{st}} = 1 - \alpha_{st} = (1 - m_{st})\left(\frac{w_t}{A_{nst}P_{st}}\right)^{\frac{\rho}{\rho-1}},$$

$$w_t = (1 - \alpha_{st})\frac{P_{st}Y_{st}}{L_{st}}.$$

- Measurement of exogenous path given the elasticity of substitution between capital and labor, $\frac{1}{1-\rho}$.

What is the role of CETC for structural change?

- Today: limiting case

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  Sector specific but constant factor shares.

  Acemoglu and Guerrieri (2008)+ sector-specific CETC.

Quantification

- Sectoral technology:

$$Y_{st} = A_{st} K_{st}^{m_s} N_{st}^{1-m_s}.$$

- Work directly with S investment goods, X_s, priced at P_{xst}:
  - inv. aggregator $\mathbf{I}_s(\{X_{jst}\}_j) \rightarrow$ optimal price index P_{xst}.

    e.g. for $\mathbf{I}_s(\{X_{js}\}_j) = \left(\sum_j \omega_{xjs}^{\frac{1}{\theta_i}} X_{jst}^{\frac{\theta_i - 1}{\theta_i}}\right)^{\frac{1}{1-\theta_i}}$, $P_{xst} = \left(\sum_j \omega_{xjs} P_{xjt}^{1-\theta_i}\right)^{\frac{1}{1-\theta_i}}$.
  - $\rightarrow$ sectoral CETC, $-\gamma_{P_{xst}}$, directly from the data.

Calibration

Levels:

Parameter			Value		Target
output elast.	σ_y		0.01		Buera et.al. (2020)
discount factor	β		0.98		Buera et.al. (2020)
depreciation rate	δ	0.14	0.21	0.17	data
labor share	$1 - m_s$	0.39	0.67	0.77	data
output shares	ω_s	0.11	0.38	0.51	employment shares, 1948
initial capital	K_{s0}	0.21	0.74	0.91	capital output ratio, 1948
initial TFP	A_{s0}	4.94	3.97	4.70	output per worker, 1948

Trends:

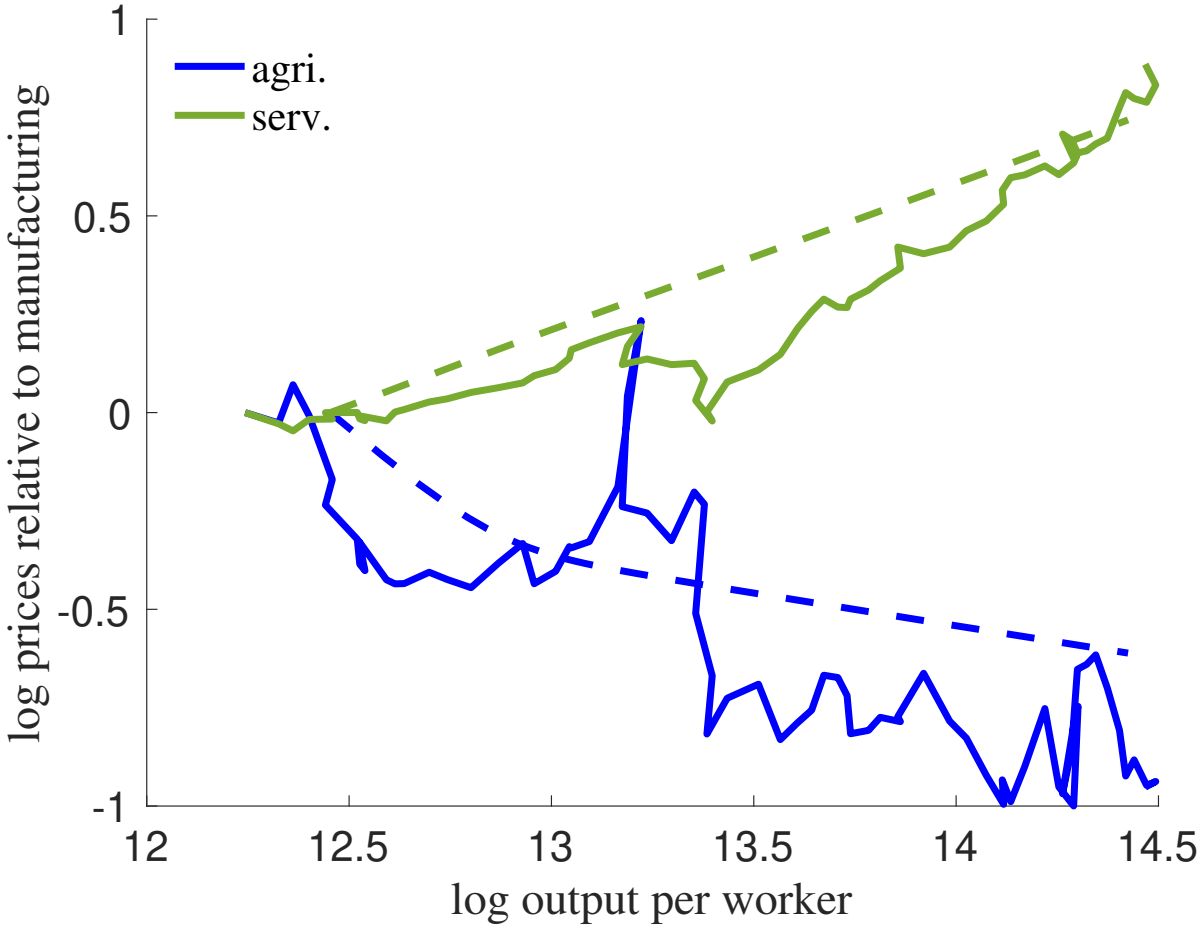
$$\gamma_{\frac{P_s}{P_{s'}}} \underbrace{=}_{\text{long-run}} \frac{1}{1 - m_s} \left(\gamma_{A_s} + \alpha_s \gamma_{A_{xs}} \right)$$

	agriculture	manufacturing	services
γ_{A_s}	0.94%	1.28%	0.41%
$\gamma_{A_{xs}}$	1.51%	2.56%	4.85%

Calibration

Model fit on targets: relative prices

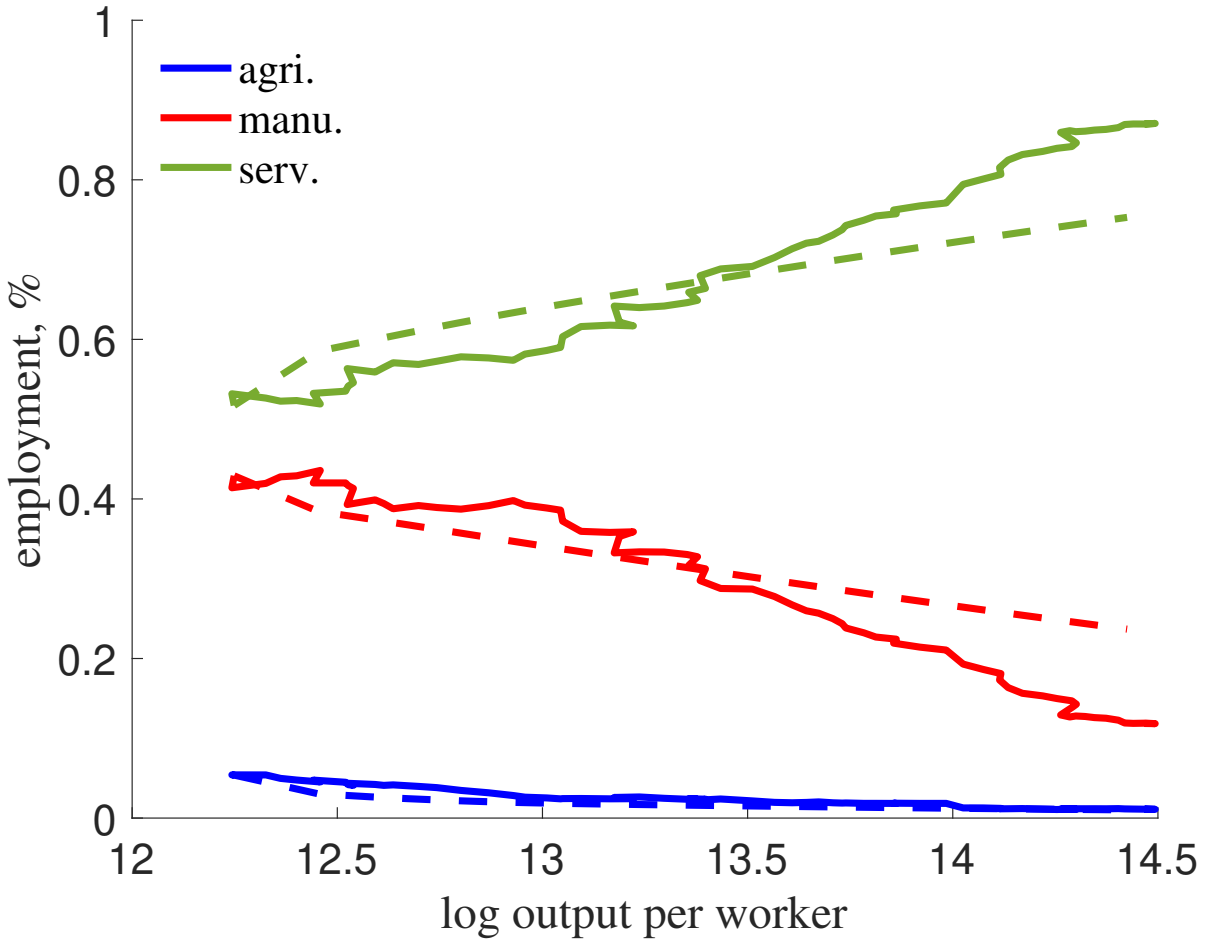
solid: data; striped: model.



Calibration

Model fit on non-targets: structural change

solid: data; striped: model.



What is the role of CETC for structural change?

Exogenous driving forces of structural change:

1. factor neutral productivity growth: sectoral γ_{A_s}.
2. CETC: sectoral $\gamma_{A_{xs}}$.
3. Acemoglu & Guerrieri: sectoral m_s.

- Counterfactual 1: **Only factor neutral**.
  - $\gamma_{Axs} = 0$ & identical m_s (=0.33).
- Counterfactual 2: **Only CETC & sectoral** m_s.
  - identical γ_{As} (=1.25%).

What is the role of CETC for structural change?

Change between 1948 and 2020, %

Prices of sectoral output relative to manufacturing.

Sector	Data	Model	Factor neutral	CETC & sectoral m_s
Agriculture	-67.78	-65.92	24.67	-79.21
Services	141.79	166.32	83.88	43.42

What is the role of CETC for structural change?

Change between 1948 and 2020, %

Employment shares.

Sector	Data	Model	Factor neutral	CETC & sectoral m_s
Agriculture	-4.24	-4.36	-1.15	-4.42
Manufacturing	-31.05	-19.22	-12.66	-6.53
Services	35.28	23.58	13.80	10.94

Capital-embodied structural change accounts for:

- 88% of the movement out of agriculture.
- 27% of the movement out of manufacturing.
- 37% of the movement into services.

Conclusion and next steps

1. Documented **systematic disparities** in the type of capital used by different sectors
   → differential CETC across sectors.

2. Productivity differentials across sectors may be (endogenously) changing:
   → Importance of the composition and timing of sectorial investment.
   → Implications for Baumol cost's disease?

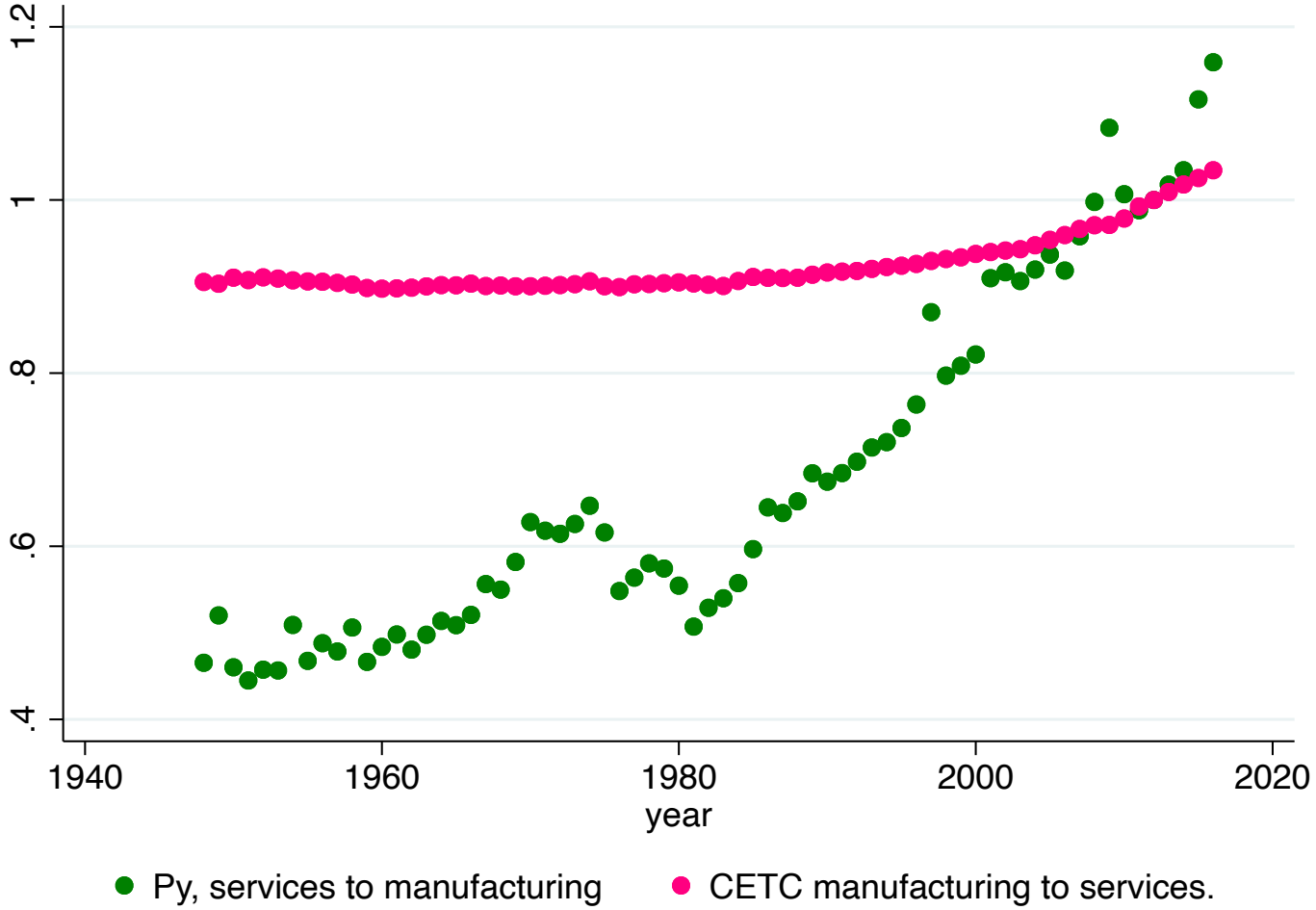
3. Next steps.
   - Results for the model with time-movement in labor shares.
   - Build time-series evidence for other countries (noticeably South Korea).

Appendix

Relative prices and CETC

Services

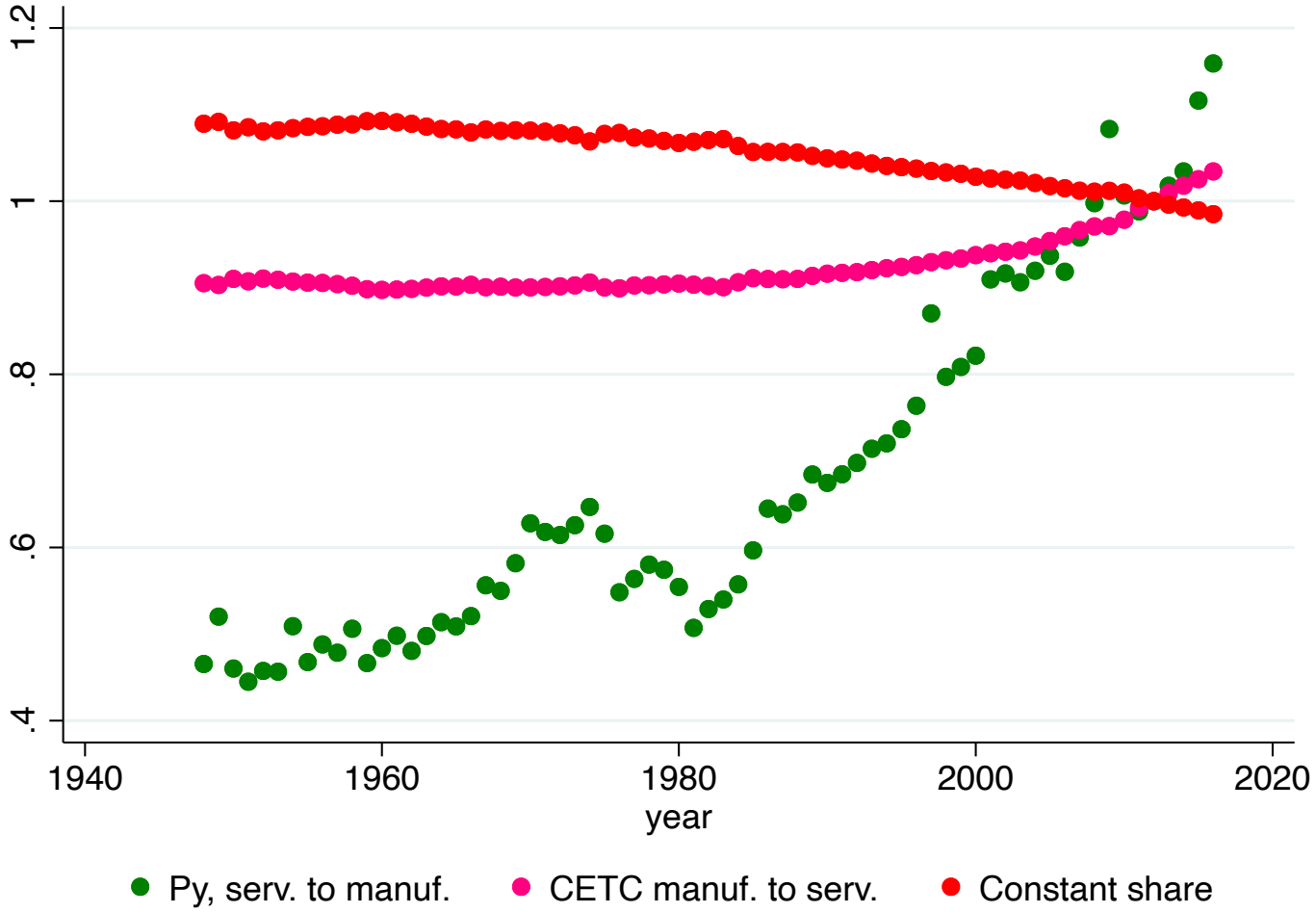
back



$$\gamma_{\frac{P_s}{P_{s'}}} \approx \left(\gamma_{\tilde{A}_{s'}} - \gamma_{\tilde{A}_s}\right) + \underbrace{\sum_j \left(\frac{\alpha_{s't}}{1-\alpha_{s't}}\kappa_{js't} - \frac{\alpha_{st}}{1-\alpha_{st}}\kappa_{jst}\right)\gamma_{A_{xjt}}}_{\text{CETC}}$$

Constant labor share

Services ▸ back



Constant share: $1 - \alpha$ set to Herrendorf, et.al. (2015).

Evidence for the US

Accounting exercise: 1986-2004 back

$$\gamma_{Y_s} = \frac{1}{1-\alpha_s}(\gamma_{A_s} + \alpha_s \gamma_{A_{xs}}).$$

Sector	γ_{A_s}	$\gamma_{A_{xs}}$	α_s, BEA	$\alpha_s \gamma_{A_{xs}}$	$\gamma_{A_s} + \alpha_s \gamma_{A_{xs}}$	CETC/Total
Agriculture	3.37	3.49	0.74	2.58	5.95	43
Manufacturing	2.23	5.26	0.40	2.10	4.33	49
Services	0.34	7.27	0.50	3.64	3.98	**91**

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Sector	γ_{A_s}	$\gamma_{A_{xs}}$	$\alpha_s, KLEMS$	$\alpha_s \gamma_{A_{xs}}$	$\gamma_{A_s} + \alpha_s \gamma_{A_{xs}}$	CETC/Total
Agriculture	3.37	3.49	0.53	1.87	5.23	36
Manufacturing	2.23	5.26	0.65	3.41	5.64	60
Services	0.34	7.27	0.34	2.48	2.83	88

Optimal allocations: Structural change

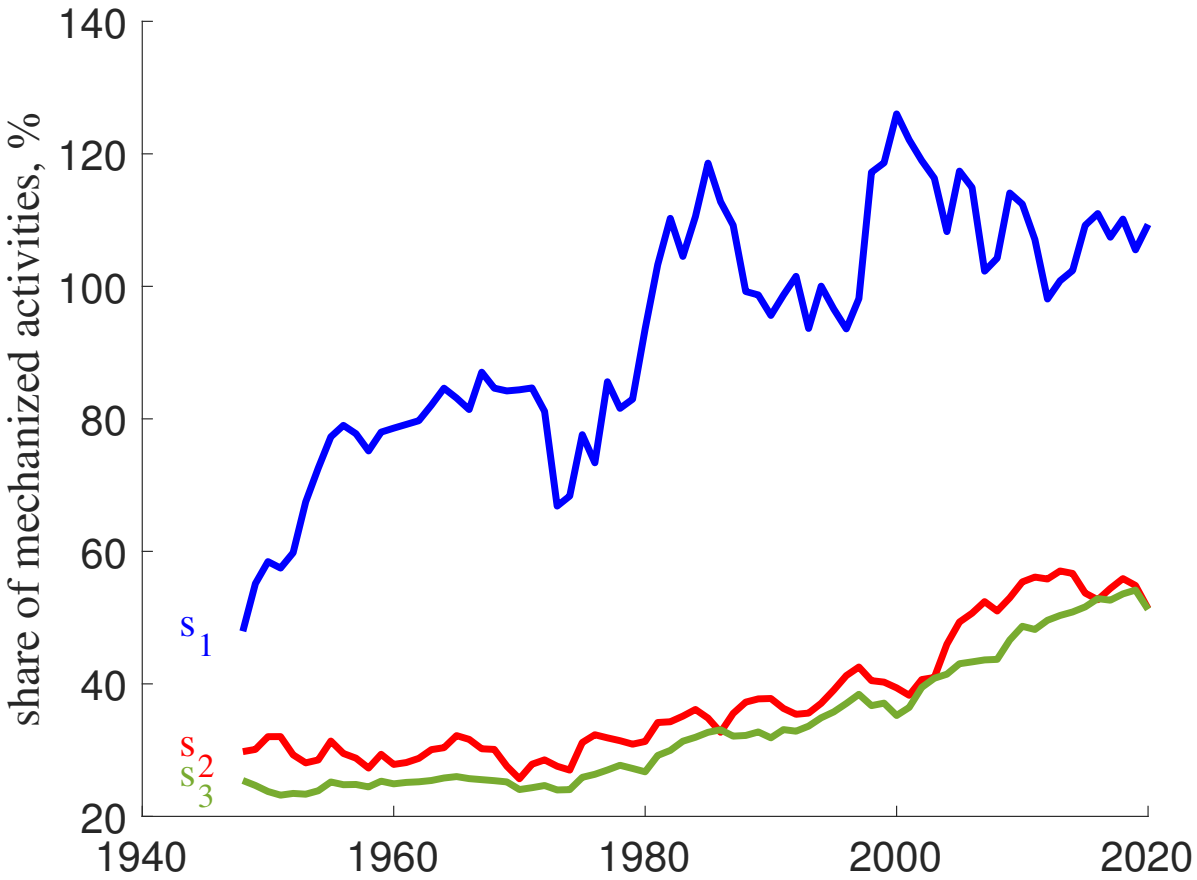
- C_t: CES sectoral goods aggregator with elasticity $\sigma_y < 1$.
- Log-preferences in consumption, $\ln(C_t)$.
- Labor allocation:

$$\begin{aligned}\frac{N_{st}}{N_{s't}} &= \frac{\omega_s}{\omega_{s'}}\left(\frac{1-\alpha_{st}}{1-\alpha_{s't}}\right)^{\sigma_y}\left(\frac{Y_{st}/N_{st}}{Y_{s't}/N_{s't}}\right)^{\sigma_y-1}, \\ &= \frac{\omega_s}{\omega_{s'}}\left(\frac{{b^n_{st}}^{(\rho-1)}}{{b^n_{s't}}^{\frac{(\rho-1)}{\rho}}}\right)^{(\sigma_y-1)}\left(\frac{\tilde{y}_{st}}{\tilde{y}_{s't}}\right)^{\sigma_y(1-\rho)-1},\end{aligned}$$

for $b^n_{st} = ((1-m_{st})Z_{st}^{-1})^{\frac{1-\rho}{\rho}}$ and $\tilde{y}_{st} = \frac{Y_{st}}{N_{st}{b^n_{st}}^{(\rho-1)}}$ or de-trended output per worker.

Along the transition: identification

Share of mechanized activities m_{st}.



blue: agriculture; red: manufacturing; green: services. ▸ ratios, ▸ additional

Along the transition: identification

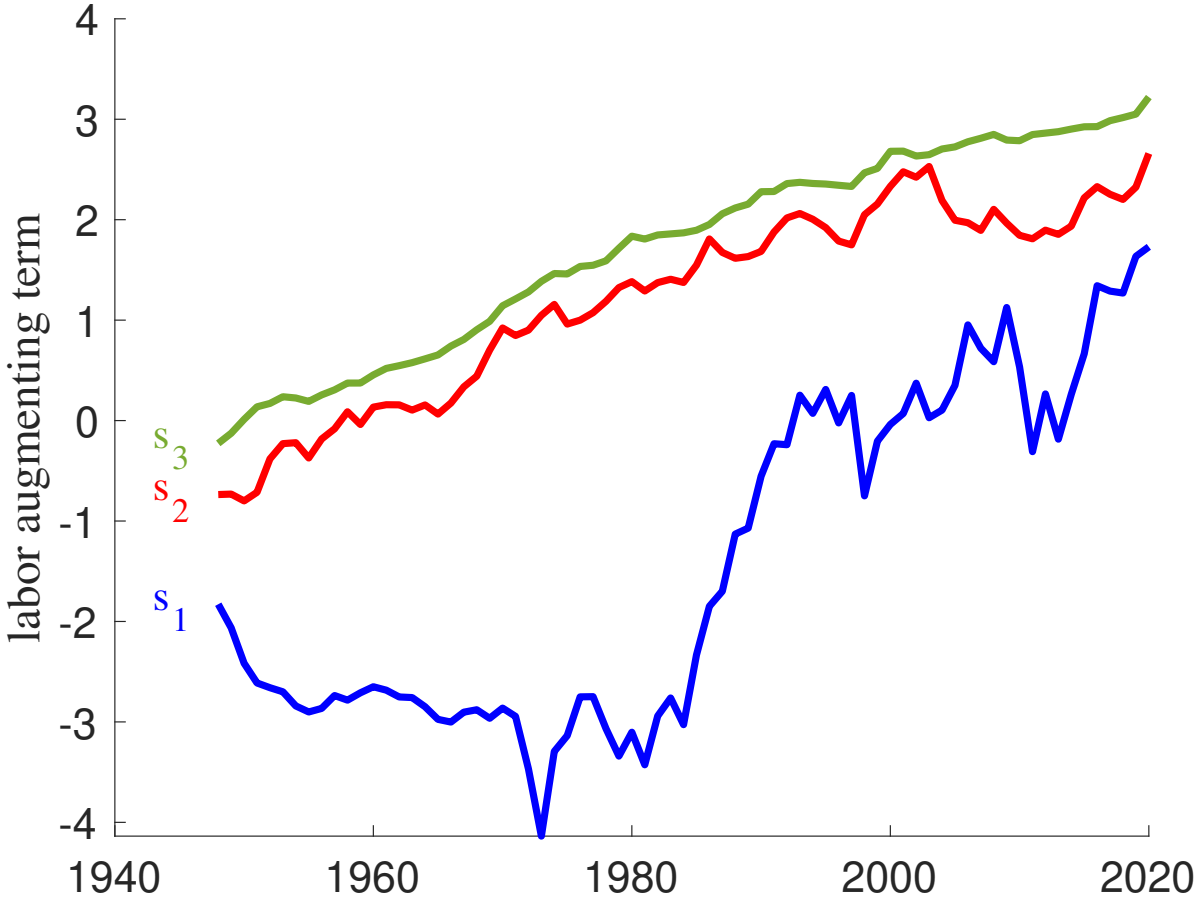
Decomposition of changes in the labor share (LS).

	σ*	CETC	change in m	change in LS	change in LS with	
					no CETC	constant m
Agriculture	1.58	1.51	61.40	-7.58	13.96	23.60
Manufacturing	0.8	2.56	21.58	-11.98	-31.50	5.57
Services	0.75	4.85	25.82	2.95	-25.82	14.27

* Source: Herrendorf, Herrington & Valentinyi (2015).

Along the transition: identification

Logs of labor augmenting technology: $\frac{1-\rho}{\rho}\log((1-m_{st})^{-1}Z_{st})$.



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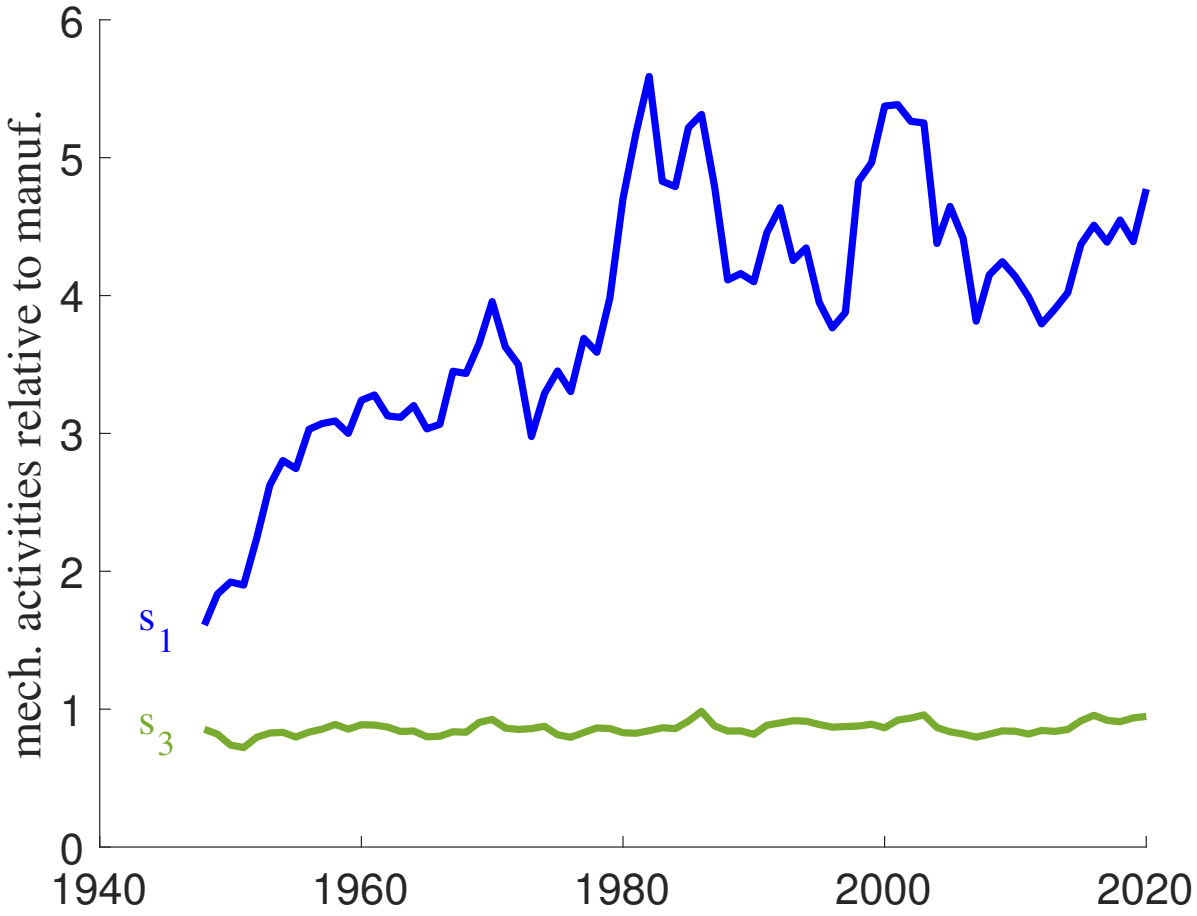
Along the transition: identification

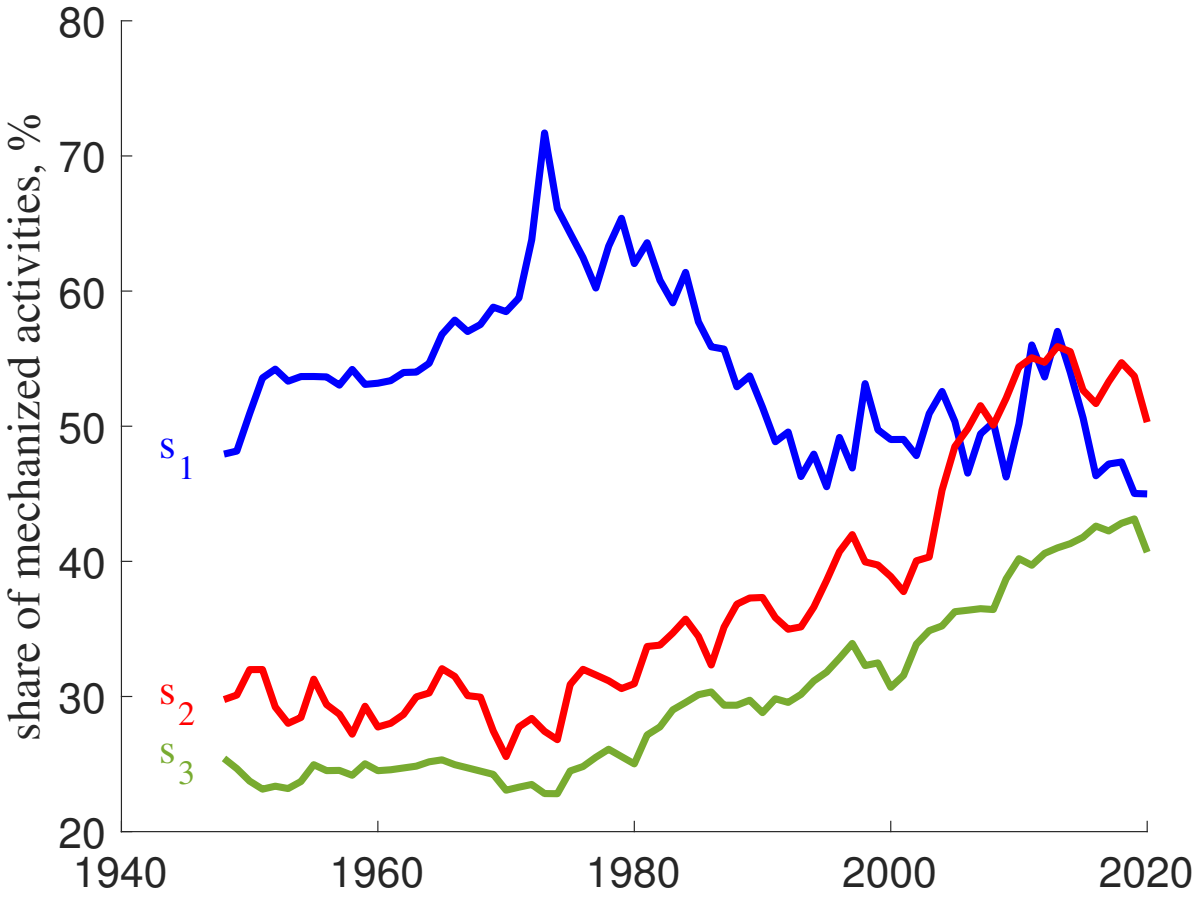
Capital intensive activities m_{st}.



blue: agriculture; green: services. levels

Along the transition: identification

Capital intensive activities m_{st}.



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Along the transition: identification

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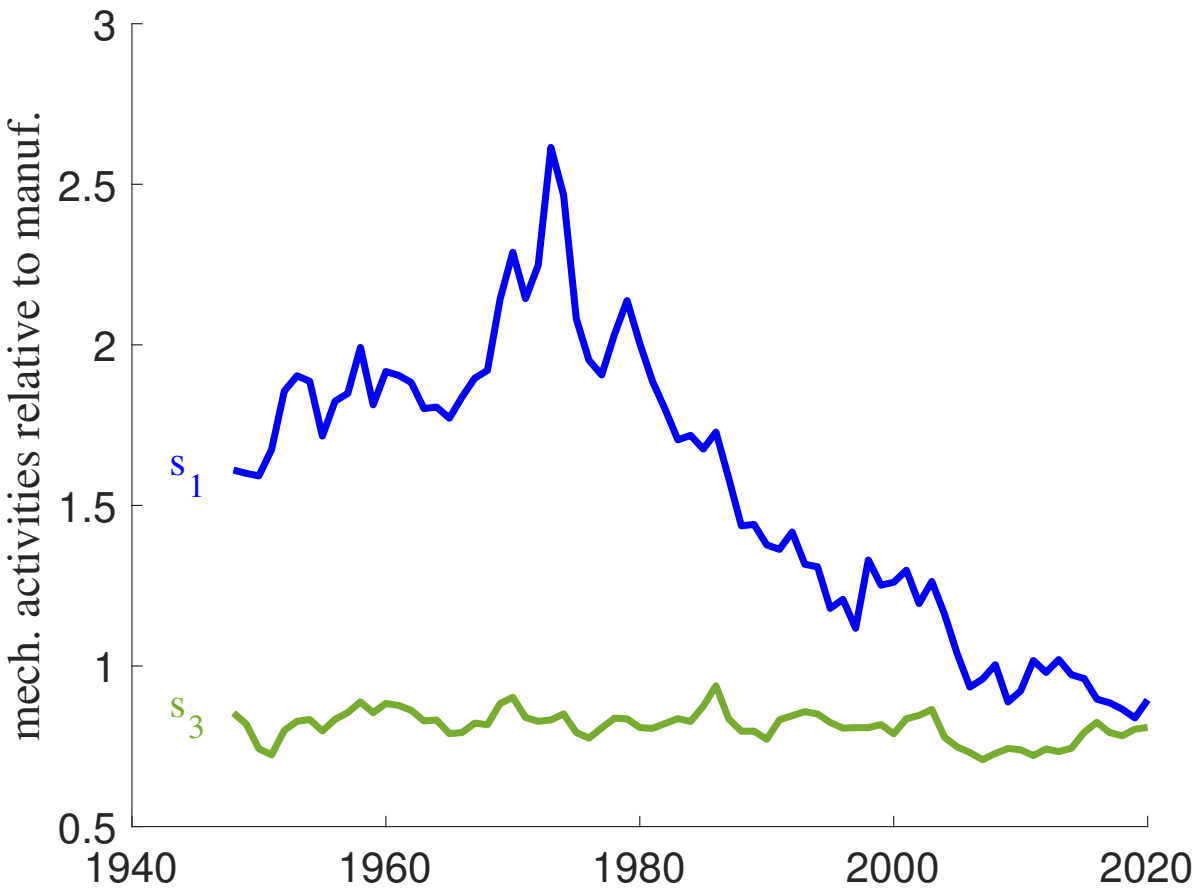


blue: agriculture; green: services. levels

Along the transition: identification

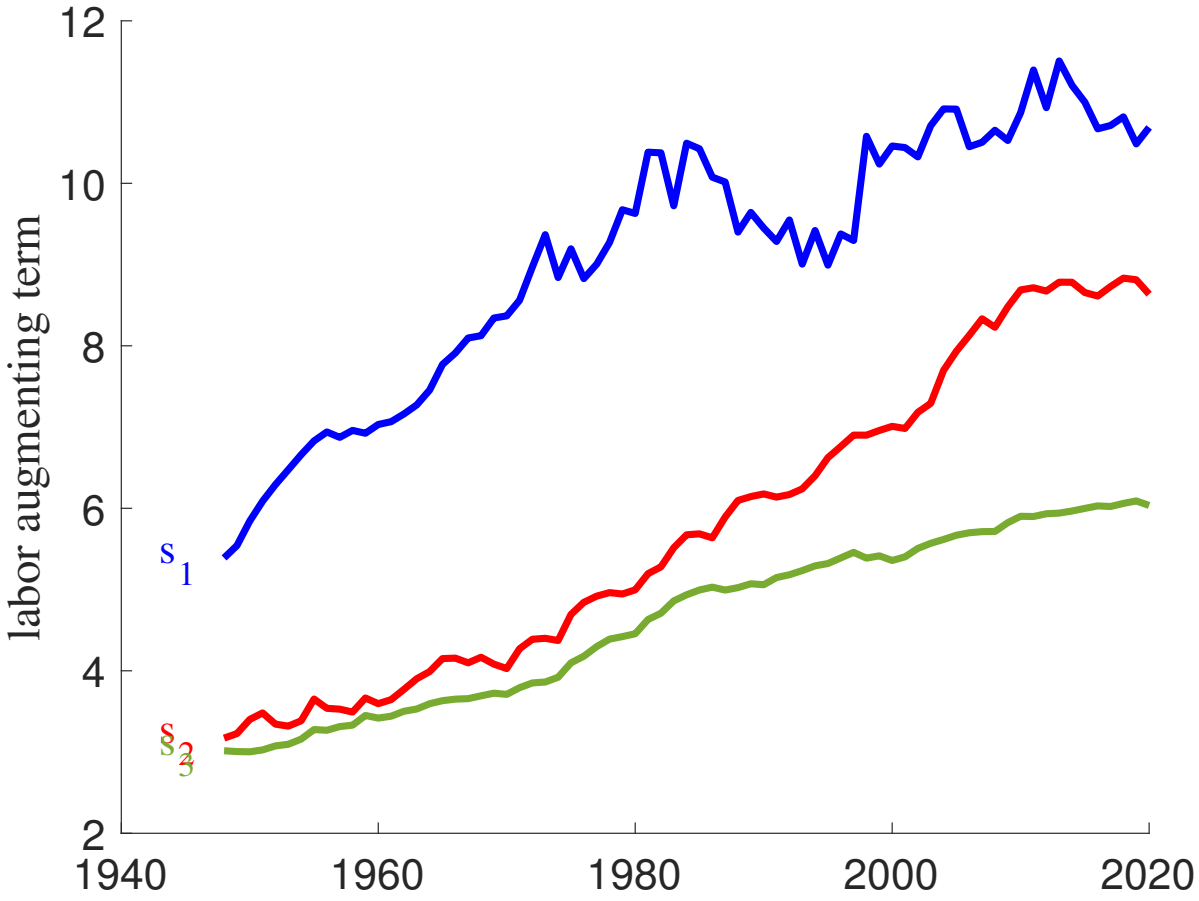
Decomposition of changes in the labor share (LS).

	σ*	CETC	change in m	change in LS	change in LS with	
					no CETC	constant m
Agriculture	0.82	1.51	-2.95	-7.58	-16.73	-11.22
Manufacturing	0.82	2.56	20.53	-11.98	-29.19	5.06
Services	0.82	4.85	15.26	2.95	-15.26	11.38

* Source: Herrendorf, Herrington & Valentinyi (2015).

Along the transition: identification

Logs of labor augmenting technology: $\frac{1-\rho}{\rho}\log((1-m_{st})^{-1}Z_{st})$.



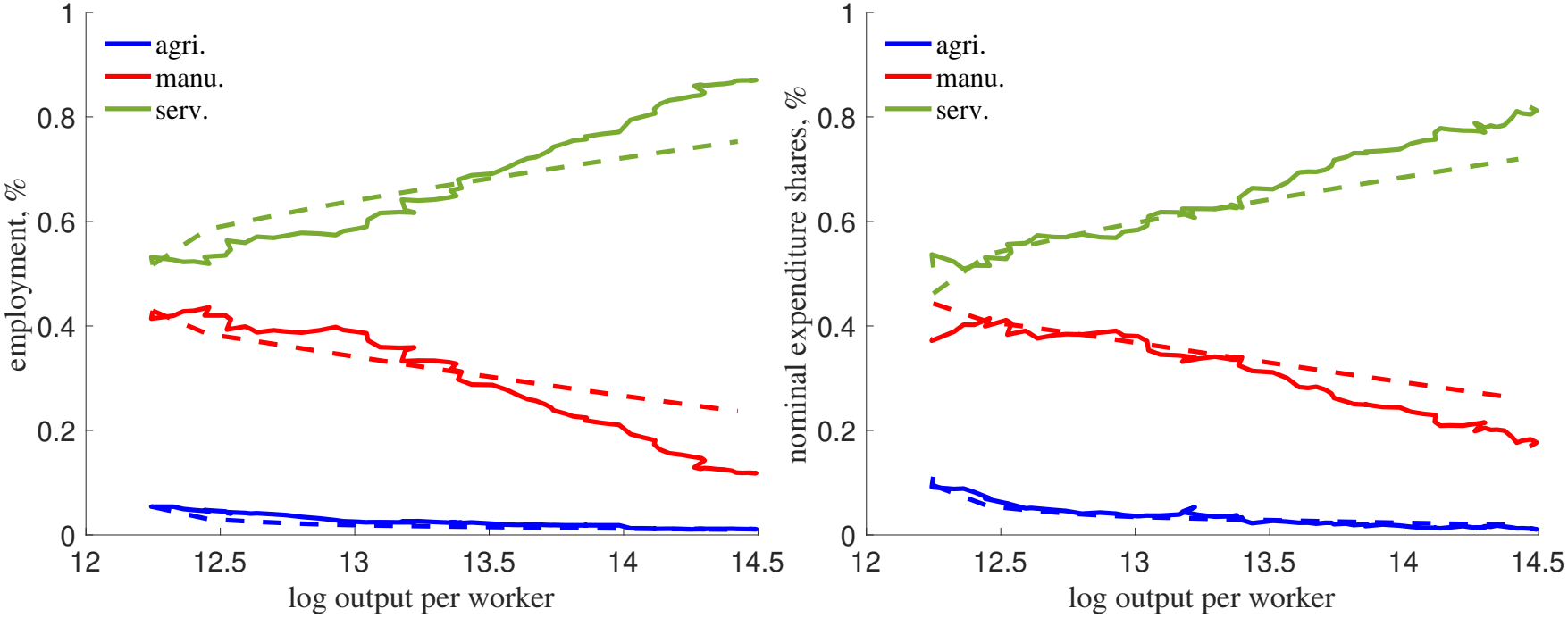
blue: agriculture; red: manufacturing; green: services.

Calibration

Model fit on non-targets: structural change

back

solid: data; striped: model



(a) employment (b) nominal expenditures

What is the role of CETC for structural change?

Change between 1948 and 2020, % back

Relative prices to manufacturing.

Sector	Data	Model	Factor neutral	CETC & sectoral m_s
Agriculture	-67.78	-65.92	24.67	-79.21
Services	141.79	166.32	83.88	43.42

Employment shares.

Sector	Data	Model	Factor neutral	CETC & sectoral m_s
Agriculture	-4.24	-4.36	-1.15	-4.42
Manufacturing	-31.05	-19.22	-12.66	-6.53
Services	35.28	23.58	13.80	10.94

Nominal expenditure shares.

Sector	Data	Model	Factor neutral	CETC & sectoral m_s
Agriculture	-9.91	-7.56	-1.15	-7.71
Manufacturing	-20.81	-18.15	-12.66	-4.86
Services	30.73	25.72	13.80	12.57