"Heterogeneous Innovation over the Business Cycle"

Early stage working paper – please do not distribute

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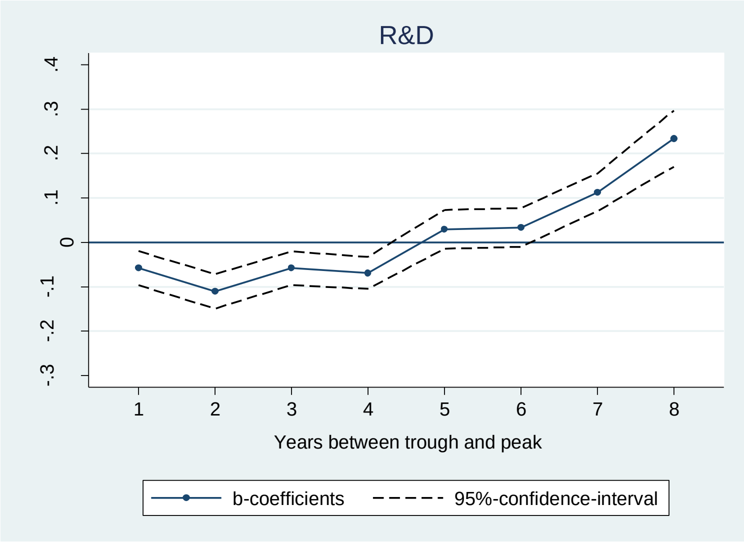
Research question

- Innovation should be countercyclical (Cooper and Haltingwanger, 1993; Caballero and Hammour, 1994; Aghion and Saint-Paul, 1998; Canton and Uhlig,1999).
- Evidence goes in the opposite direction:



- Credit constraints (Aghion et al 2007); risk aversion (Rampini 2004); externalities in R&D (Barlevy 2007);

This Paper

- Different types of innovation (exploration versus exploitation)
- Theoretical model exploration and exploitation over the business cycle
  - Exploration is countercyclical, exploitation is procyclical
- Develop clear metrics of firm level exploration/exploitation
  - Principal component anlysis (PCA) of readily available patent portfolio measures
- Validate these measures against some outcomes
- Study exploration and exploitation over the business cycle

The Model Without Macro Shocks

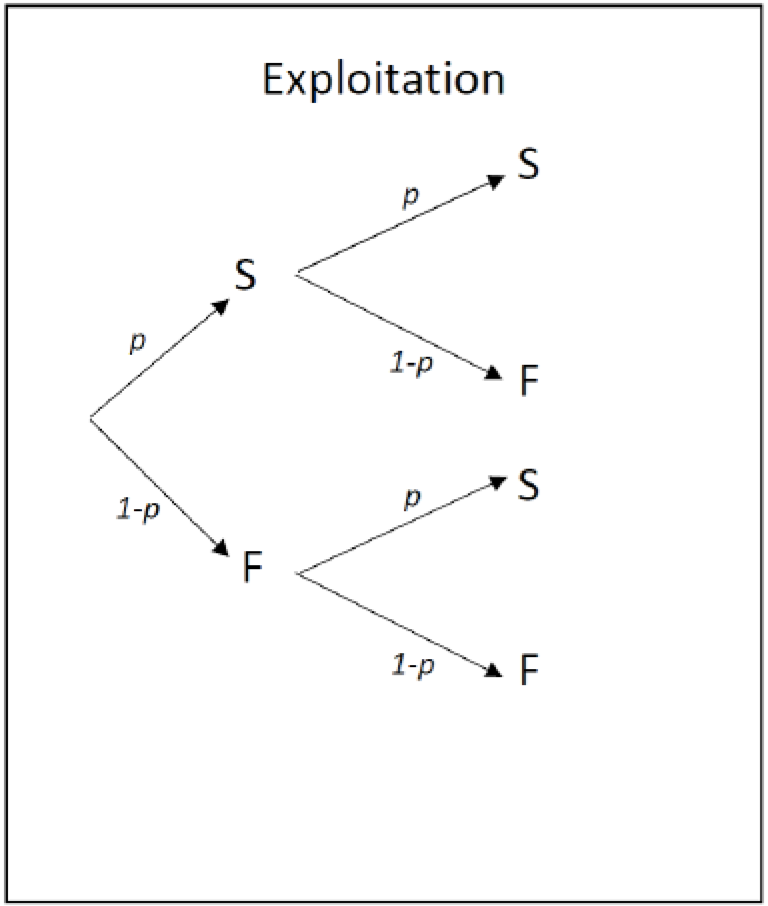
- Agents live two periods and are risk neutral with zero discounting
- Representative firm chooses between a well-known or a novel action
- Well-known action has a known probability p of success. Novel action has an unknown probability q of success.
- The novel action is of exploratory nature:

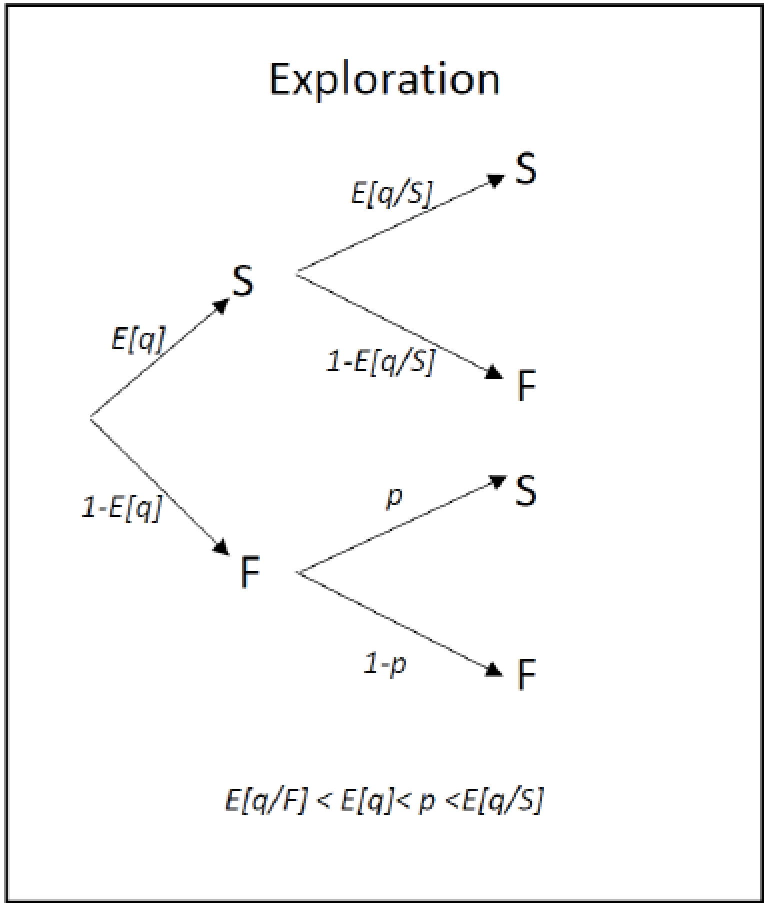
$$E[q]<p<E[q|S]$$

Action Plans

- Only two action plans need to be considered
  - Exploitation: take the well known action in both periods
  - Exploration: take the novel action in the first period and stick to it only if success is obtained.

Action Plans





Optimal Choice

- Exploration is better than exploitation iff

$$E[q] \geq \frac{1}{(1 + (E[q|S] - p))} p$$

- More periods? Teams?

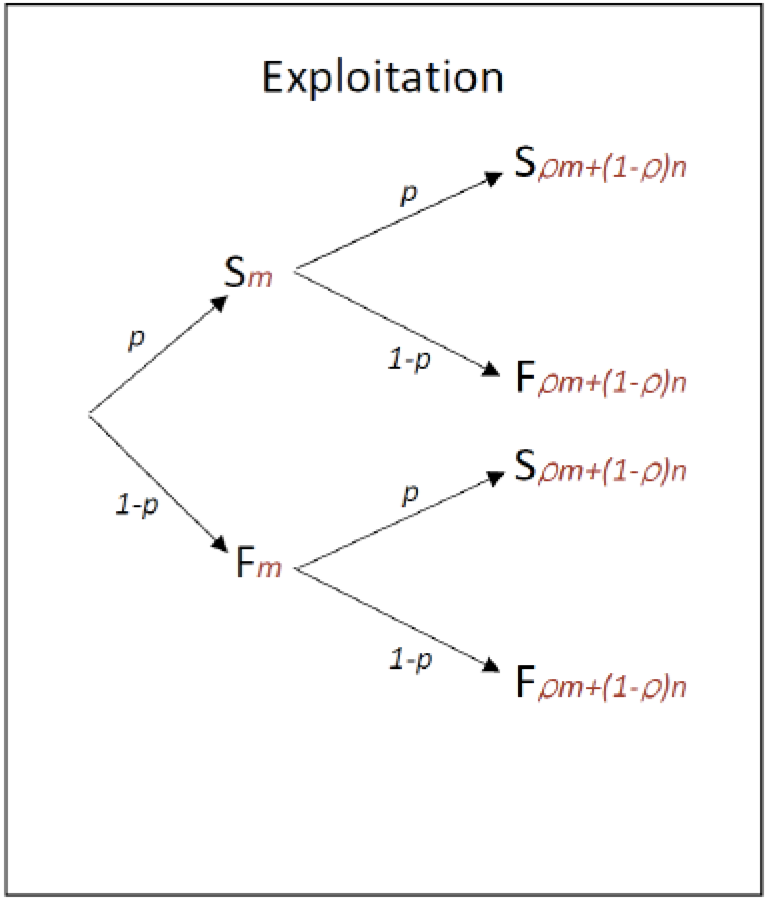
Adding Macro Shocks to the Model

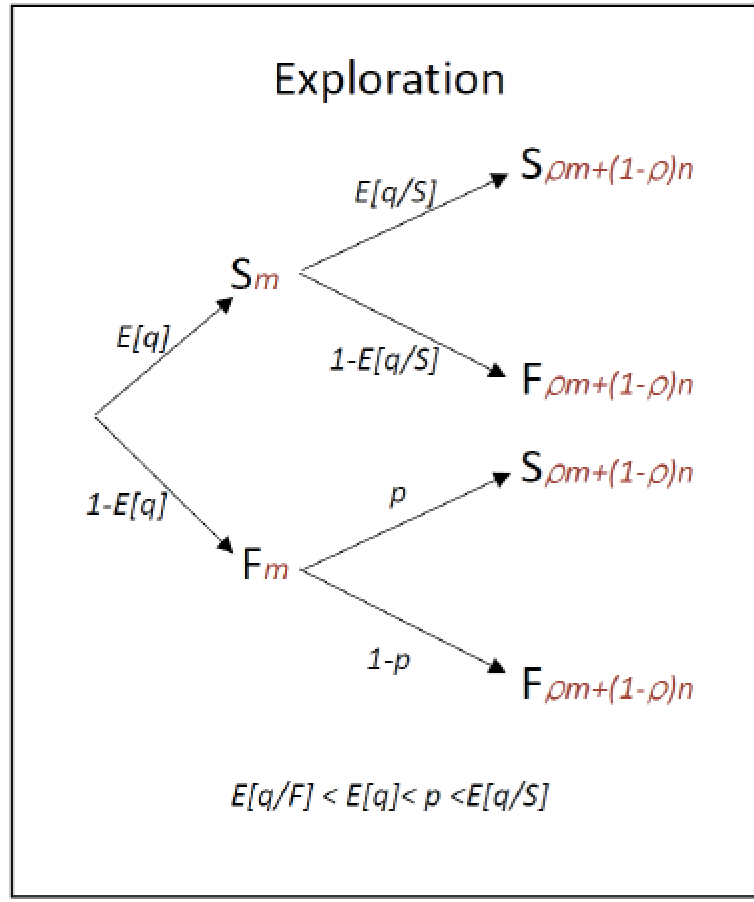
- Macroeconomic state *m* can be either high (H) or low (L)

- If the macroeconomic state is *m* it remains in the same state next period with probability ρ_m. Alternatively it transitions into the other state *n* next period.

- Output in each period is given by *mS* in case of success and *mF* in case of failure.

Action Plans





Payoffs

- Exploitation:

$$pmS + (1-p)mF + \rho_m\left(pmS + (1-p)mF\right) + (1-\rho_m)(pnS + (1-p)nF)$$

- Exploration:

$$E[q]mS + (1-E[q])mF + \rho_m\Big(E[q](E[q|S]mS + (1-E[q|S]))mF) + (1 - E[q])(E[q|F]mS + (1-E[q|F])mF)\Big) + (1-\rho_m)(E[q](E[q|S]nS + (1-E[q|S])nF) + (1-E[q])(pnS + (1-p)nF))$$

Optimal Choice

- Exploration is better than exploitation iff:

$$E[q] \geq \frac{m}{n(E[q|S]-p)(1-\rho_m) + m(1+(E[q|S]-p)\rho_m)}\, p$$

- The threshold is increasing in m and decreasing in n.
  - –Exploration more common in recessions
  - –Exploitation more common in booms

Optimal Choice

- Exploration is better than exploitation iff:

$$E[q] \geq \frac{m}{n(E[q|S]-p)(1-\rho_m) + m(1+(E[q|S]-p)\rho_m)} p$$

- The threshold is increasing in ρ_L and decreasing in ρ_H.
  - –Exploration less common if recessions are long-lasting
  - –Exploration more common if booms are long-lasting

For now just 1977-2001

Table 1 – Frequency count of firm-year patent portfolio observations.

Year	Frequency	Percent	Cum.
1977	718	2.97	2.97
1978	718	2.97	5.94
1979	747	3.09	9.03
1980	756	3.13	12.16
1981	765	3.17	15.33
1982	770	3.19	18.52
1983	763	3.16	21.67
1984	783	3.24	24.91
1985	831	3.44	28.35
1986	832	3.44	31.8
1987	855	3.54	35.34
1988	873	3.61	38.95
1989	844	3.49	42.44
1990	877	3.63	46.07
1991	937	3.88	49.95
1992	1,024	4.24	54.19
1993	1,106	4.58	58.76
1994	1,191	4.93	63.69
1995	1,348	5.58	69.27
1996	1,315	5.44	74.71
1997	1,347	5.57	80.29
1998	1,323	5.48	85.76
1999	1,232	5.1	90.86
2000	1,141	4.72	95.58
2001	1,067	4.42	100
Total:	**24,163**	**100**	

Table 2 – Summary statistics

Variable	N	mean	Median	sd	min	max
Patents	24163	34.26	4	137.2	1	4054
Top 1%	24163	0.484	0	1.795	0	41
Top 5-2%	24163	1.601	0	5.813	0	164
Top 10-6%	24163	2.457	0	8.665	0	258
Top 25-11%	24163	7.381	1	27.35	0	845
Top 50-26%	24163	11.70	2	45.38	0	1365
No cite	24163	1.693	0	8.834	0	278
All future cites	24163	669.1	77	2882	0	120444
New tech classes entered	24163	2.539	1	4.559	0	89
Patents in new classes	24163	3.016	1	6.183	0	185
Patents in known classes	24163	31.25	3	134.4	0	4051
Technological proximity	24163	0.541	0.581	0.328	0	1
Av. age of inventors	24163	3.633	3.063	3.131	0	26
Backward citations	24163	331.0	41	1387	0	48540
Self-citations	24163	42.55	1	280.6	0	11413
Claims	24163	528.5	66	2357	1	85704
Patent stock	24163	312.7	23	1279	0	34942

Notes: This table reports summary statistics of variables used in the study. Patents is the total number of eventually granted patents applied for in a given year. Top 1% are the number of patents that fall into the 1% most cited patents within a given 3-digit technology class and application year. Top 5% to 2% are the number of patents that fall into the 5% to 2% most cited patents within a given 3-digit technology class and application year. Top 10% to 6% are the number of patents that fall into the 10% to 6% most cited patents within a given 3-digit technology class and application year. Top 25% to 11% are the number of patents that fall into the 25% to 11% most cited patents within a given 3-digit technology class and application year. Top 50% to 26% are the number of patents that fall into the 50% to 26% most cited patents within a given 3-digit technology class and application year. 'No cite' are the number of patents that are not cited by any other patent. All future cites is the total number of future citations. New classes entered is the number of technology classes where a firm filed at least one patent but no other patent beforehand. Patents in new/known classes is the number of patents that are filed in classes where the given firm has filed no/at least one other patent beforehand. Technological proximity is the technological proximity between the patents filed in year t to the existing patent portfolio held by the same firm up to year *t*-1, calculated according to Jaffe (1989). Av. Age of inventors the average time difference between the first time an inventor occurs in the Fung Institute's patent database and the application year of a given patent. Backward citations is the total number of citations made to other patents. Self-citations is the total number of cites to patents held by the same firm. Claims is the total number of claims on each patent. Patent stock is the sum of all patents held by a given firm up to the year *t*-1.

Table 3 - Correlation matrix

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
(1)	Patents	1.00															
(2)	Top 1%	0.66	1.00														
(3)	Top 5-2%	0.80	0.73	1.00													
(4)	Top 10-6%	0.84	0.80	0.82	1.00												
(5)	Top 25-11%	0.92	0.68	0.87	0.83	1.00											
(6)	Top 50-26%	0.95	0.69	0.78	0.88	0.86	1.00										
(7)	No cite	0.76	0.55	0.65	0.67	0.70	0.73	1.00									
(8)	All future cites	0.87	0.65	0.77	0.81	0.87	0.85	0.55	1.00								
(9)	New tech classes entered	0.71	0.45	0.55	0.58	0.64	0.67	0.52	0.61	1.00							
(10)	Patents in new classes	0.71	0.45	0.55	0.59	0.64	0.67	0.52	0.62	0.99	1.00						
(11)	Patents in known classes	0.97	0.64	0.78	0.82	0.90	0.93	0.75	0.84	0.56	0.56	1.00					
(12)	Technological proximity	0.32	0.17	0.23	0.25	0.29	0.30	0.19	0.32	-0.03	-0.03	0.42	1.00				
(13)	Av. age of inventors	0.15	0.07	0.11	0.12	0.14	0.14	0.12	0.15	-0.07	-0.06	0.21	0.17	1.00			
(14)	Backward citations	0.91	0.59	0.73	0.77	0.85	0.87	0.64	0.85	0.62	0.63	0.89	0.33	0.22	1.00		
(15)	Self-citations	0.87	0.63	0.75	0.78	0.84	0.85	0.68	0.77	0.47	0.47	0.89	0.35	0.27	0.85	1.00	
(16)	Claims	0.94	0.61	0.75	0.79	0.87	0.89	0.68	0.86	0.65	0.65	0.91	0.33	0.20	0.91	0.84	1.00
(17)	Patent stock	0.83	0.53	0.65	0.69	0.76	0.79	0.66	0.68	0.46	0.45	0.87	0.19	0.27	0.77	0.82	0.78

Notes: This table reports pairwise correlations of the log-transformed variables used in the study. Patents is the total number of eventually granted patents applied for in a given year. Top 1% are the number of patents that fall into the 1% most cited patents within a given 3-digit technology class and application year. Top 5% to 2% are the number of patents that fall into the 5% to 2% most cited patents within a given 3-digit technology class and application year. Top 10% to 6% are the number of patents that fall into the 10% to 6% most cited patents within a given 3-digit technology class and application year. Top 25% to 11% are the number of patents that fall into the 25% to 11% most cited patents within a given 3-digit technology class and application year. Top 50% to 26% are the number of patents that fall into the 50% to 26% most cited patents within a given 3-digit technology class and application year. 'No cite' are the number of patents that are not cited by any other patent. All future cites is the total number of future citations. New classes entered is the number of technology classes where a firm filed at least one patent but no other patent beforehand. Patents in new/known classes is the number of patents that are filed in classes where the given firm has filed no/at least one other patent beforehand. Technological proximity is the technological proximity between the patents filed in year t to the existing patent portfolio held by the same firm up to year *t*-1, calculated according to Jaffe (1989). Av. Age of inventors the average time difference between the first time an inventor occurs in the Fung Institute's patent database and the application year of a given patent. Backward citations is the total number of citations made to other patents. Self-citations is the total number of cites to patents held by the same firm. Claims is the total number of claims on each patent. Patent stock is the sum of all patents held by a given firm up to the year *t*-1.

Tables 4 and 5 – Principal Component Analysis

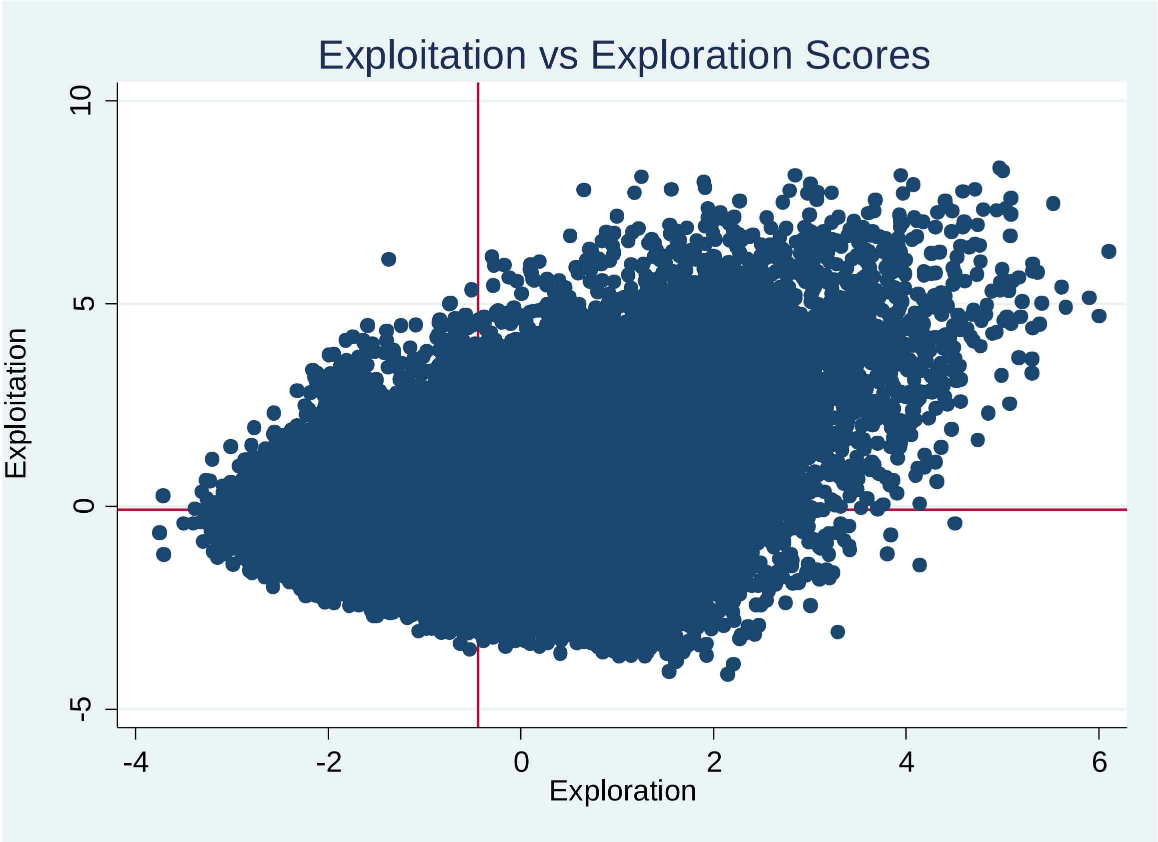
Component	Variance	Difference	Proportion	Cumulative
Comp1	4.02	1.72	0.50	0.50
Comp2	2.30		0.29	0.79

Notes: This table reports the results of a Principal Component Analysis after Varimax Rotation. Only components with Eigenvalues above one are extracted. The 8 variables that entered the PCA are: new classes entered, patents in new/known classes, technological proximity, av. age of inventors, backward citations, self-citations, and claims; all variables log-transformed.

Variable	Comp1	Comp2	Unexplained
New tech classes entered		0.58	0.08
Patents in new classes		0.58	0.08
Patents in known classes	0.45		0.09
Technological proximity	0.39	-0.38	0.47
Backward citations	0.41		0.10
Self-citations	0.45		0.16
Claims	0.41		0.09
Av. age of inventors	0.31	-0.37	0.60

Notes: This table reports the results of a Principal Component Analysis after Varimax Rotation. Only components with Eigenvalues above one are extracted. All variables log-transformed. Variable definitions provided above.

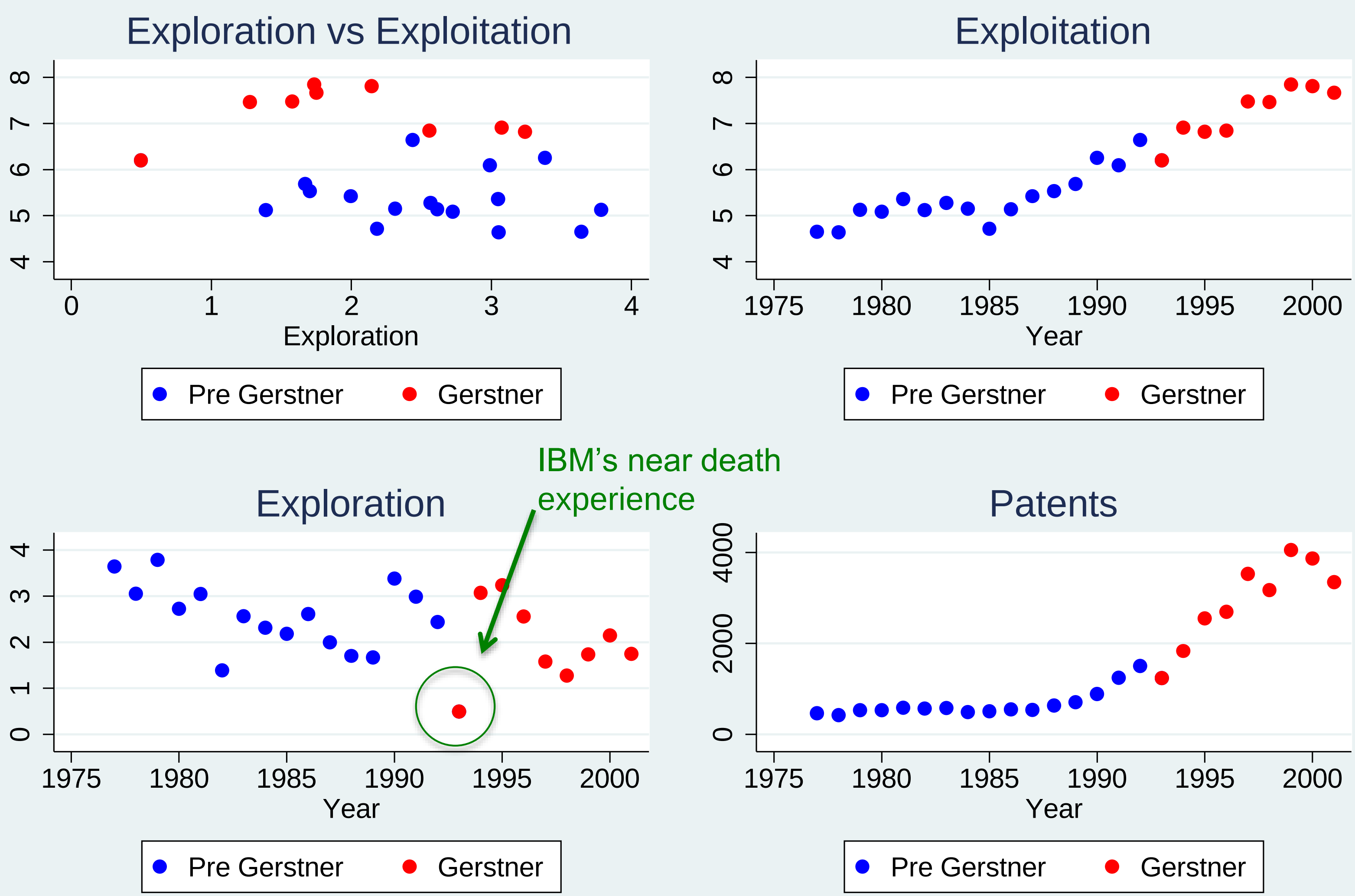
Figure 1 – Scatter Plot of PCA scores



Median of factor

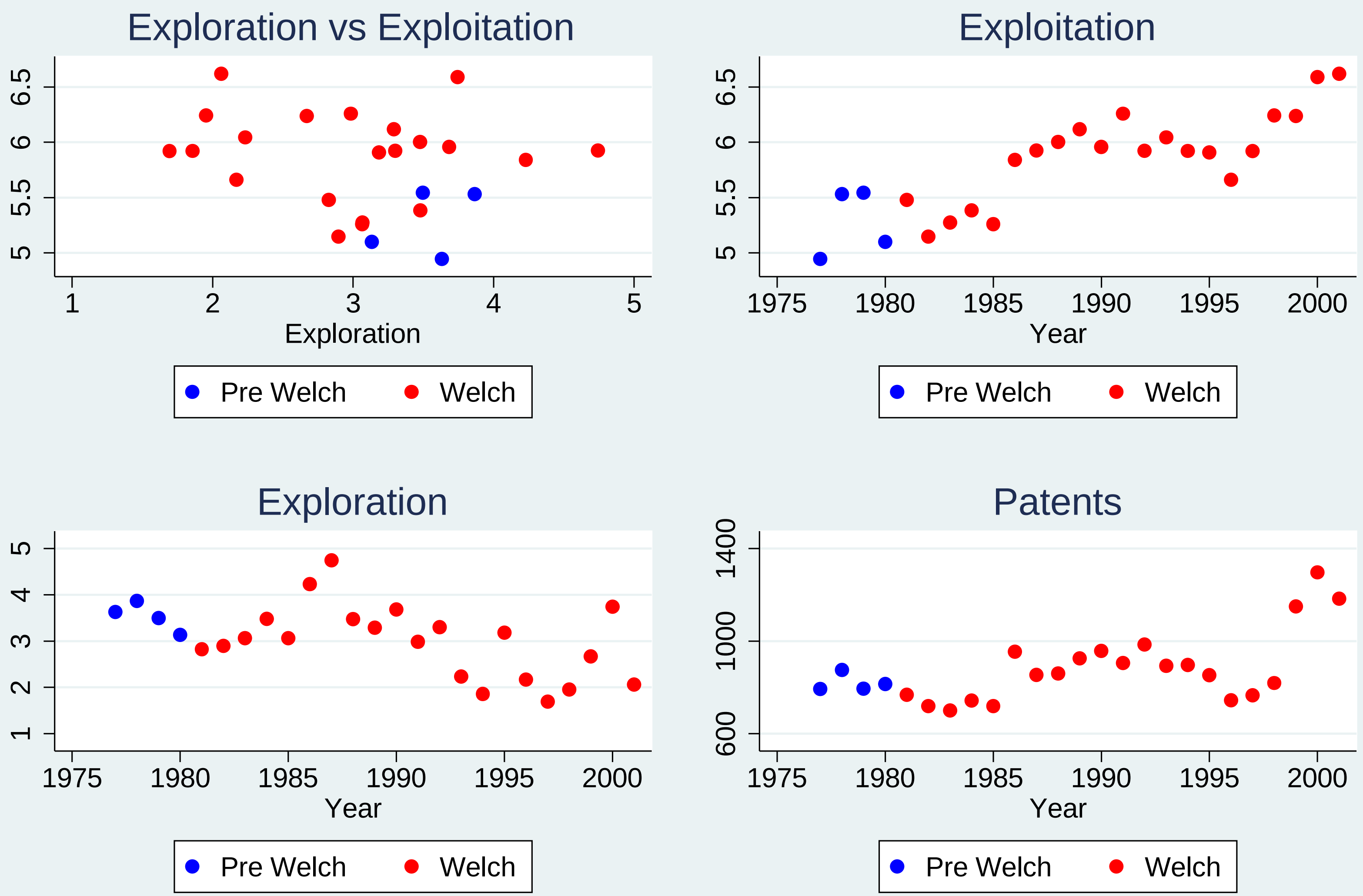
Notes: This graph plots the component scores of 'Exploration' and 'Exploitation' extracted from the Principal Component Analysis shown above. Red lines mark the median values of each factor. 19% of the observations are each in the upper left and lower right quadrants, 31% in each of the other quadrants.

IBM



Exploration vs Exploitation
Exploration
Exploitation
Year
Exploration
Patents
IBM's near death experience
Pre Gerstner
Gerstner

GE


Exploration vs Exploitation
6.5
6
5.5
5
1
2
3
4
5
Exploration
Pre Welch
Welch
Exploitation
6.5
6
5.5
5
1975
1980
1985
1990
1995
2000
Year
Pre Welch
Welch
Exploration
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4
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2
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1975
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1985
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Patents
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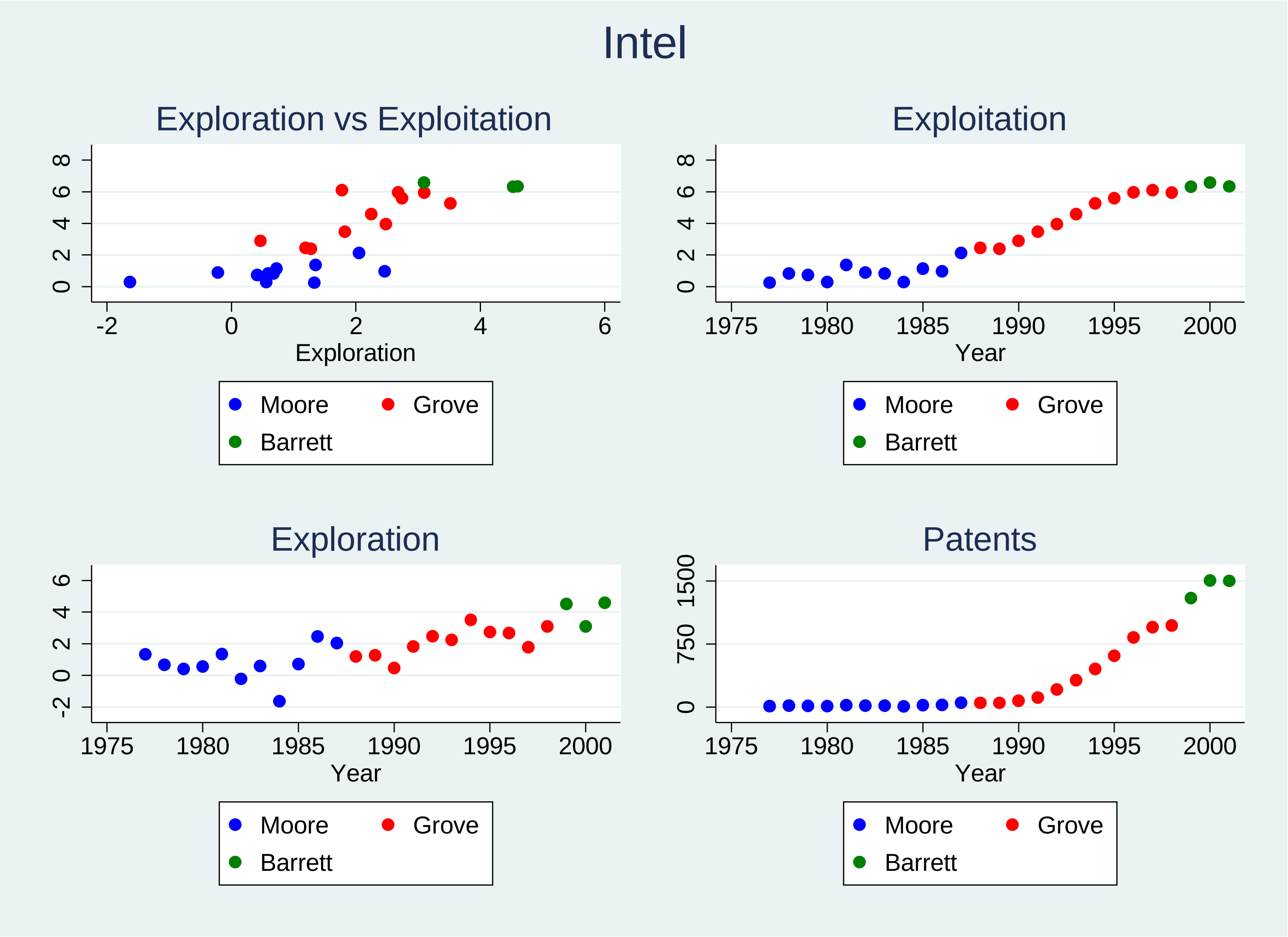
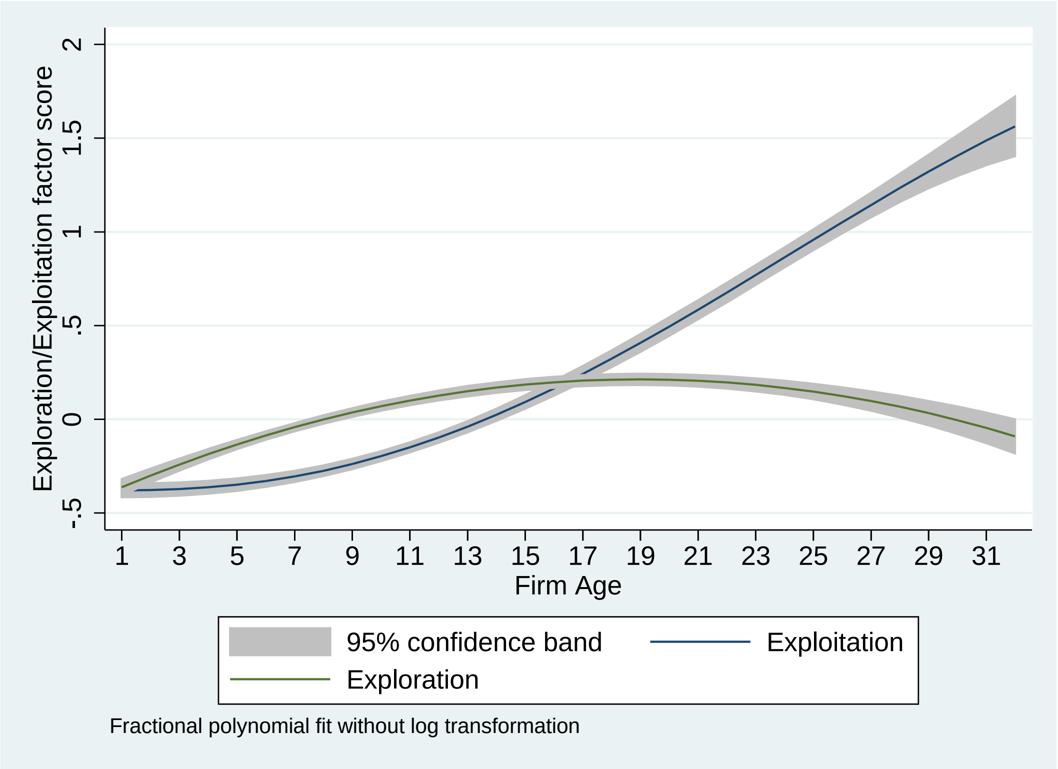
Year
Pre Welch
Welch



Intel
Exploration vs Exploitation
Exploration
Exploitation
Year
Exploration
Patents
Moore
Grove
Barrett

An inexorable exploitation path dependence (except of course for Intel)?



Exploitation

Exploration

Table 7 - Patent citation distribution break out

	a	b	c	d	e	f	g
Dependent variable	**Top 1%**	**Top 5-2%**	**Top 10-6%**	**Top 25-11%**	**Top 50-26%**	**Not cited**	**All future cites**
log(patent stock)	0.104***	0.182***	0.212***	0.278***	0.307***	0.207***	0.352***
	(0.008)	(0.011)	(0.011)	(0.012)	(0.011)	(0.011)	(0.014)
R&D	0.163***	0.246***	0.281***	0.364***	0.367***	0.144***	0.652***
	(0.032)	(0.046)	(0.049)	(0.066)	(0.060)	(0.029)	(0.152)
log(age)	-0.031***	-0.065***	-0.073***	-0.100***	-0.103***	-0.085***	-0.201***
	(0.007)	(0.010)	(0.010)	(0.011)	(0.011)	(0.011)	(0.017)
log(total assets)	0.027***	0.055***	0.059***	0.087***	0.099***	0.067***	0.104***
	(0.005)	(0.006)	(0.006)	(0.007)	(0.007)	(0.006)	(0.011)
Exploit	-0.072***	-0.042**	0.005	0.225***	0.292***	-0.189***	1.129***
	(0.014)	(0.020)	(0.021)	(0.022)	(0.021)	(0.019)	(0.033)
Explore	0.009*	0.017**	0.036***	0.093***	0.148***	0.003	0.441***
	(0.005)	(0.008)	(0.009)	(0.011)	(0.012)	(0.007)	(0.024)
Exploit + Explore	0.112***	0.319***	0.468***	0.884***	1.018***	0.078***	2.069***
	(0.017)	(0.023)	(0.024)	(0.026)	(0.025)	(0.022)	(0.037)
Time + Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	24163	24163	24163	24163	24163	24163	24163
R^2	0.323	0.489	0.550	0.686	0.739	0.520	0.668

Notes: This tables presents OLS regression results. All dependent variables are log-transformed. Top 1% are the number of patents that fall into the 1% most cited patents within a given 3-digit technology class and application year. Top 5% to 2% are the number of patents that fall into the 5% to 2% most cited patents within a given 3-digit technology class and application year. Top 10% to 6% are the number of patents that fall into the 10% to 6% most cited patents within a given 3-digit technology class and application year. Top 25% to 11% are the number of patents that fall into the 25% to 11% most cited patents within a given 3-digit technology class and application year. Top 50% to 26% are the number of patents that fall into the 50% to 26% most cited patents within a given 3-digit technology class and application year. 'No cite' are the number of patents that are not cited by any other patent. All future cites is the total number of future citations. R&D is R&D expenditures scaled by total assets. Age is years since IPO. 'Exploit'/'Explore' indicates all firms focusing on exploitation/exploration, as classified by the PCA shown above. 'Exploit+Explore' indicates all firms that score high (>median) on both components. All categories are mutually exclusive. Time fixed effects are 23 dummies for each year. Industry fixed effects are 25 dummies for each 2-digit-SIC industry. All models include an intercept which is omitted in the table. Standard errors clustered at the firm level appear in parentheses. ***, ** and * indicate a significance level of 1%, 5%,

Table 8 – Performance regressions

	a	b
Dependent variable	**Capital Productivity**	**Labor Productivity**
log(patent stock)$_{t\text{-}1}$	0.011	0.017**
	(0.007)	(0.007)
R&D $_{t\text{-}1}$	-0.957***	-0.639***
	(0.081)	(0.106)
log(age) $_{t\text{-}1}$	-0.048***	0.086***
	(0.010)	(0.011)
log(total assets) $_{t\text{-}1}$		0.935***
		(0.008)
log(employees) $_{t\text{-}1}$	0.987***	
	(0.008)	
Exploit $_{t\text{-}1}$	0.005	-0.054**
	(0.018)	(0.022)
Explore $_{t\text{-}1}$	0.048***	0.049***
	(0.013)	(0.015)
Exploit + Explore $_{t\text{-}1}$	0.123***	0.045**
	(0.020)	(0.022)
Time + Industry FE	Yes	Yes
N	20707	20707
R^2	0.943	0.917

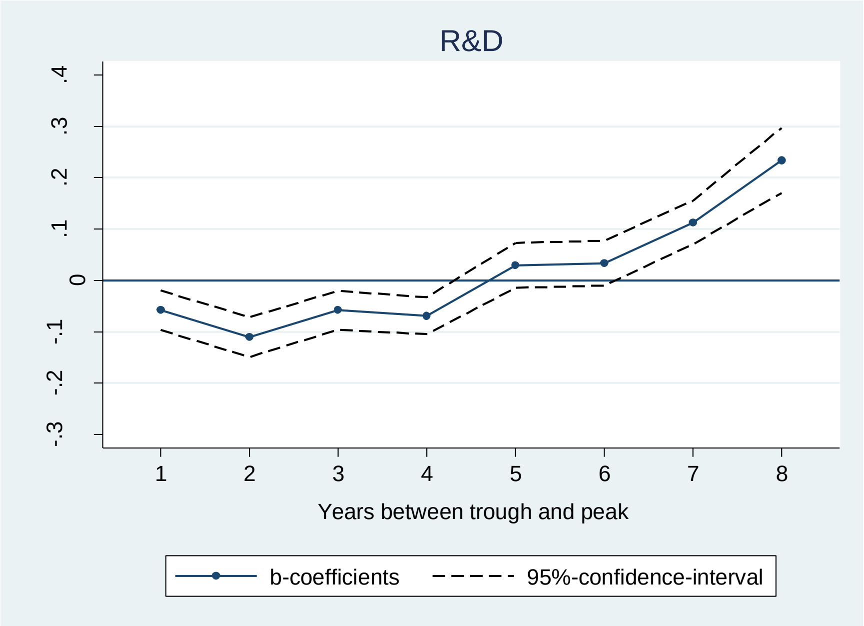
Notes: This tables presents OLS regression results. All dependent variables are log-transformed and winsorized by year at the 1% level. Patent stock are all eventually granted patents applied for up to year *t*-1. R&D is R&D expenditures scaled by total assets. Age is years since IPO. 'Exploit'/'Explore' indicates all firms focusing on exploitation/ exploration, as classified by the PCA shown above. 'Exploit+Explore' indicates all firms that score high (>median) on both components. All categories are mutually exclusive. Time fixed effects are 23 dummies for each year. Industry fixed effects are 25 dummies for each 2-digit-SIC industry. All models include an intercept which is omitted in the table. Standard errors clustered at the firm level appear in parentheses. ***, ** and * indicate a significance level of 1%, 5%, and 10%, respectively.

Table 9 – Market Entry and Product Proximity Regressions

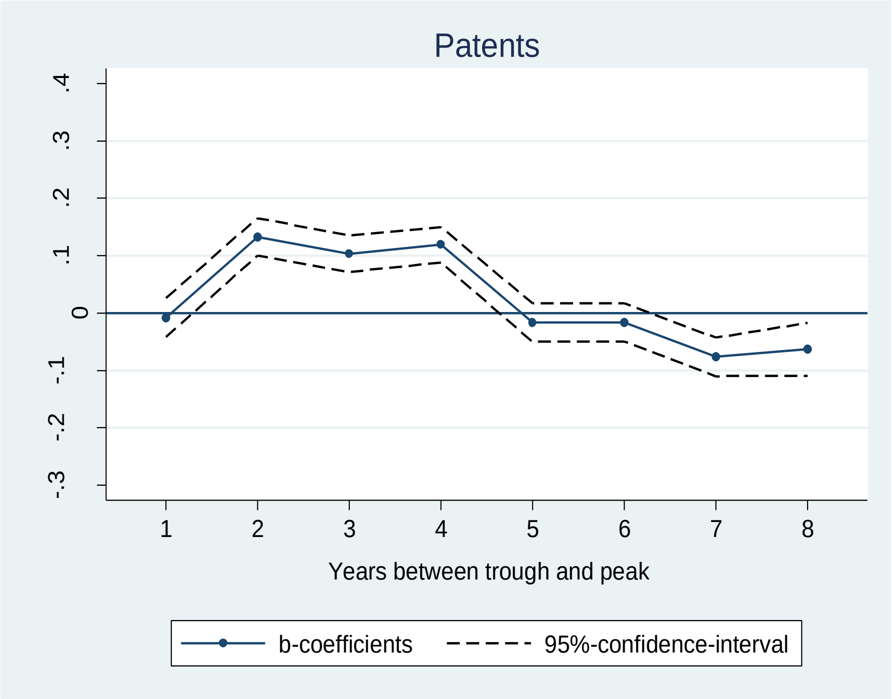
	a	b	c	d
Dependent variable	**Entry 0/1**	**Log(No. Entries)**	**log(new sales)**	**Prod. Proximity**
log(patent stock)$_{t-1}$	-0.002	0.000	0.034	-0.010***
	(0.013)	(0.004)	(0.024)	(0.003)
R&D$_{t-1}$	-0.073	0.007	0.341***	0.222***
	(0.146)	(0.021)	(0.077)	(0.025)
log(age)$_{t-1}$	-0.025	-0.011**	-0.070**	-0.025***
	(0.020)	(0.005)	(0.030)	(0.004)
log(total assets)$_{t-1}$	0.103***	0.030***	0.312***	0.007***
	(0.013)	(0.003)	(0.020)	(0.003)
Exploit$_{t-1}$	-0.090**	-0.024***	-0.187***	0.038***
	(0.039)	(0.008)	(0.048)	(0.008)
Explore$_{t-1}$	0.095***	0.019***	0.061*	-0.009*
	(0.032)	(0.007)	(0.035)	(0.006)
Exploit + Explore$_{t-1}$	0.070*	0.008	0.050	0.024***
	(0.042)	(0.010)	(0.063)	(0.008)
Time + Industry FE	Yes	Yes	Yes	Yes
N	2287	2287	2287	5800
R^2		0.118	0.173	0.346

Notes: All dependent variables are measured in t+1 to t+3. Model (a) is a Probit model where the dependent variable indicates if a given firm enters at least one new product market, defined as the first time appearance of positive sales in a given 3-digit SIC industry where the firm has not generated sales previously. Model (b) is an OLS regression of the logarithm of (no. entries + 1). Model (c) is an OLS regression of the logarithm of (new sales +1), where new sales is the total amount of sales generated in all new industries. Model (d) is an OLS regression of product proximity based on textual analysis of firms' 10k fillings by Hoberg and Phillips (2015, 2010), multiplied by 100 to give it a proportional value. Patent stock is the cumulative number of patents applied for since 1976. 'Exploit'/'Explore' indicates all firms focusing on exploitation/ exploration, as classified by the PCA shown above. 'Exploit+Explore' indicates all firms that score high (>median) on both components. All categories are mutually exclusive. All models include an intercept which is omitted in the table. Heteroscedasticity-robust standard errors are clustered at the firm level and shown in parentheses. ***, **, * indicate statistical significance at the 1%, 5%, 10% level, respectively.

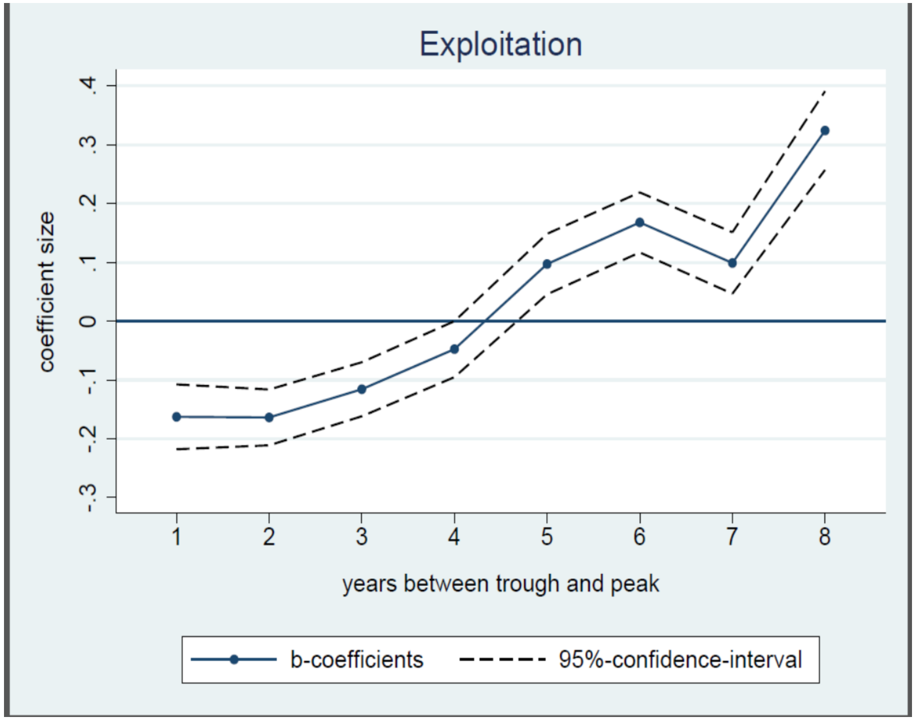
Innovation Over the Business Cycle

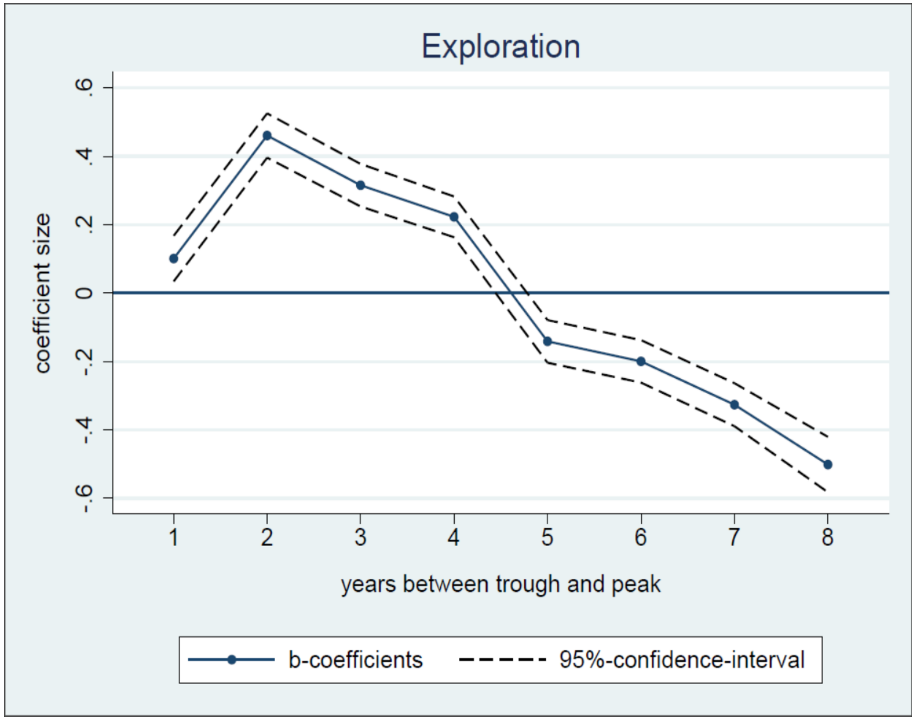


Innovation Over the Business Cycle

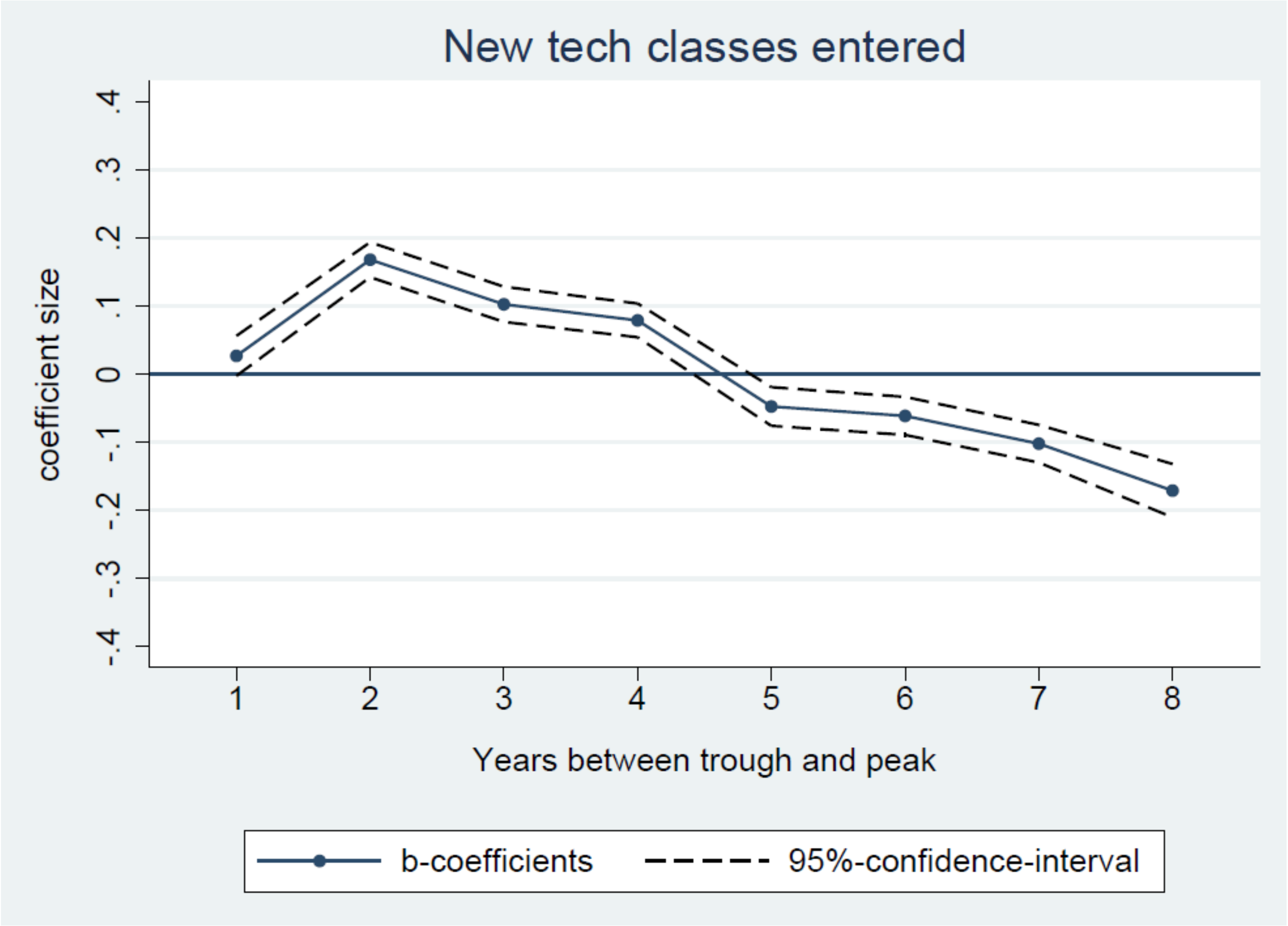


Exploration/Exploitation over the Business Cycle

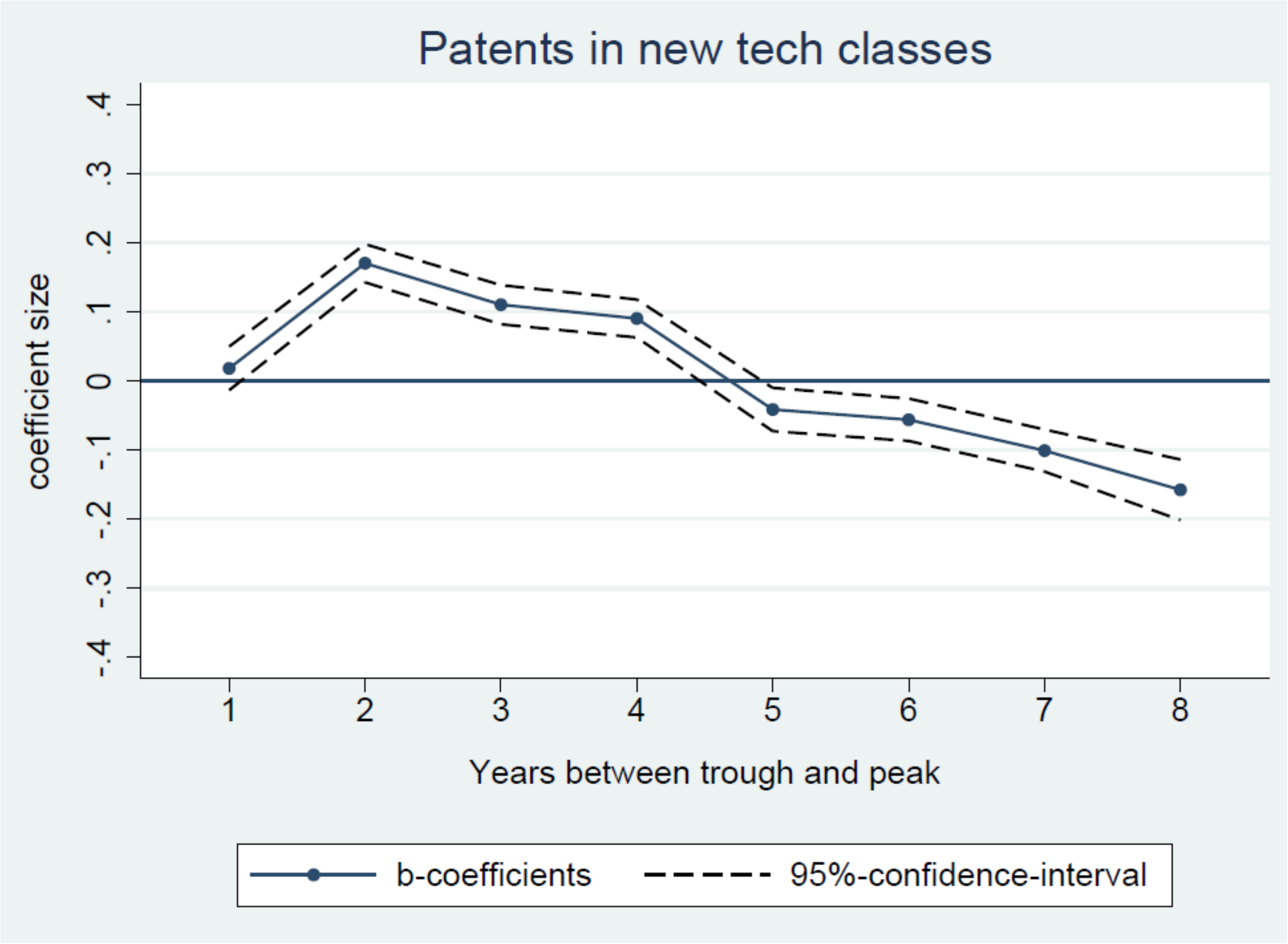




Individual Components over the Business Cycle



Individual Components over the Business Cycle



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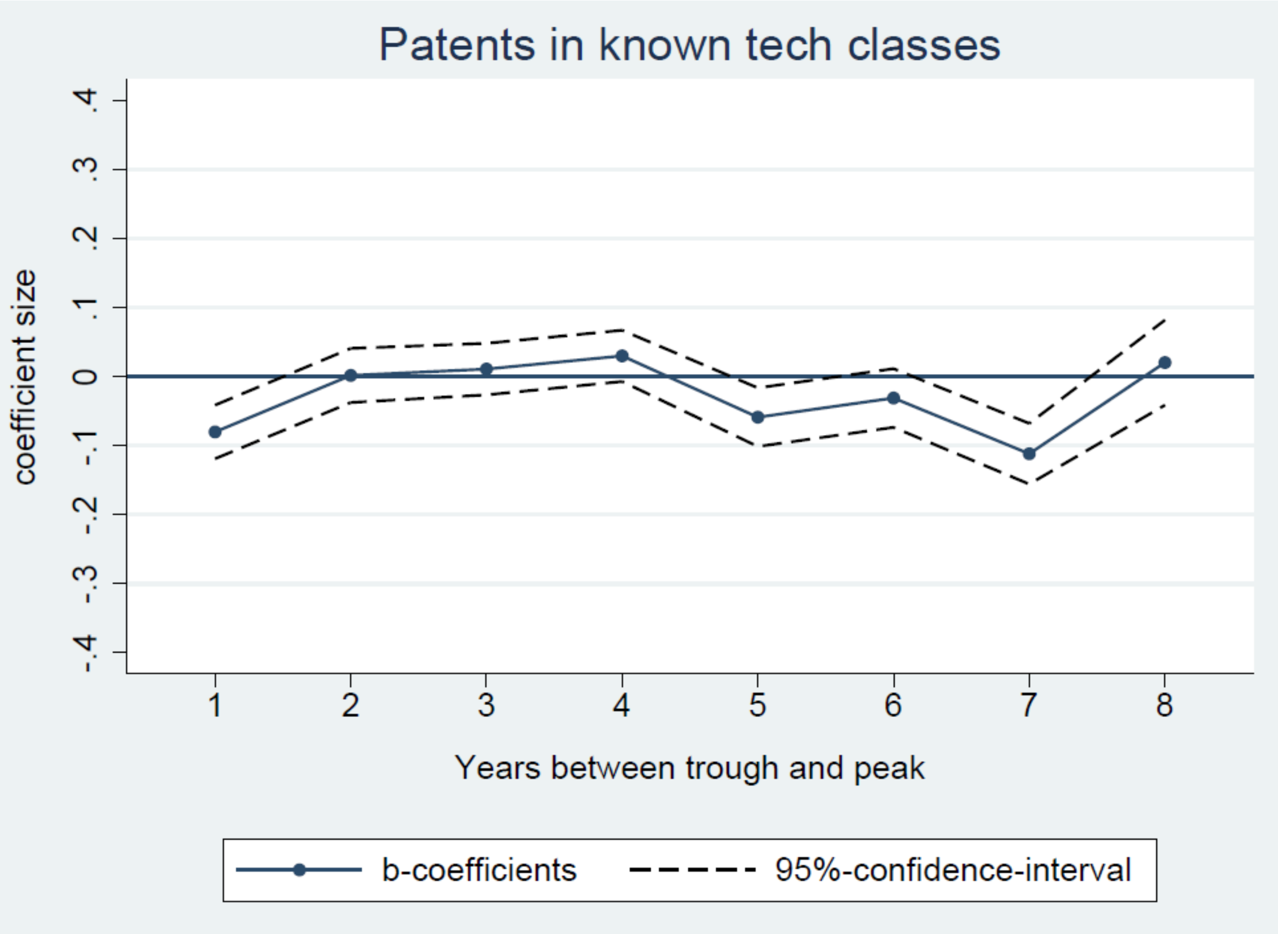

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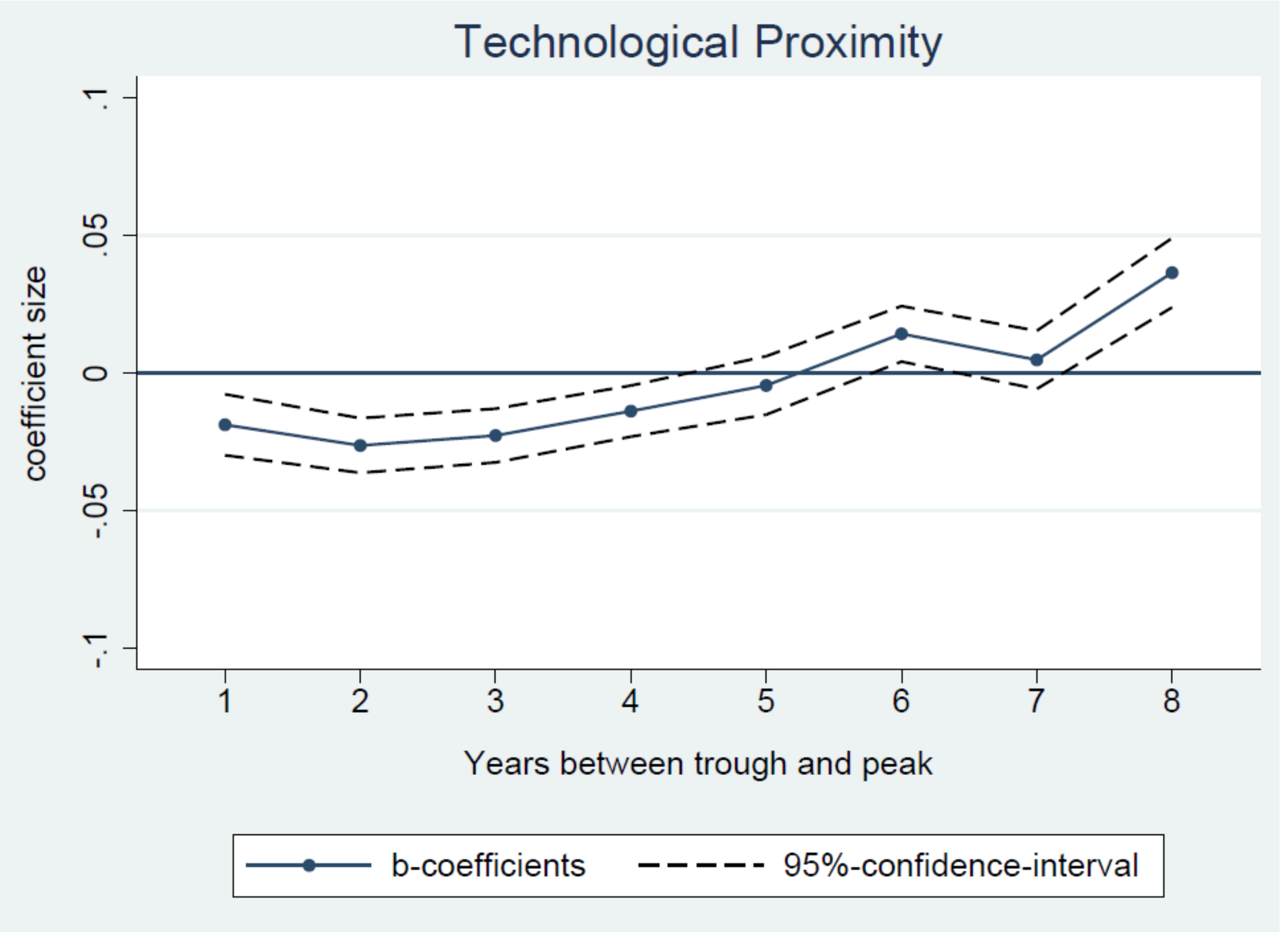
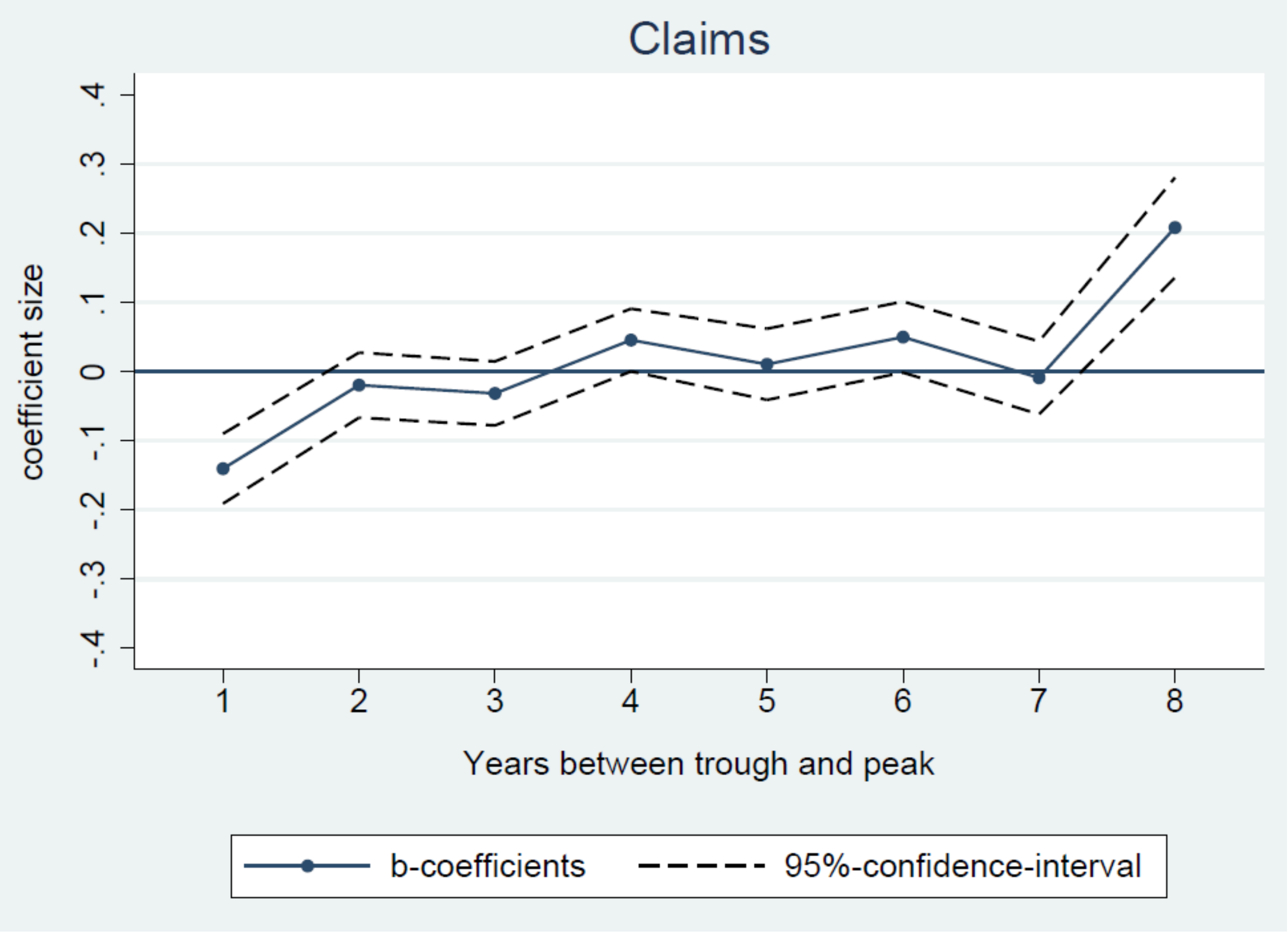


Individual Components over the Business Cycle



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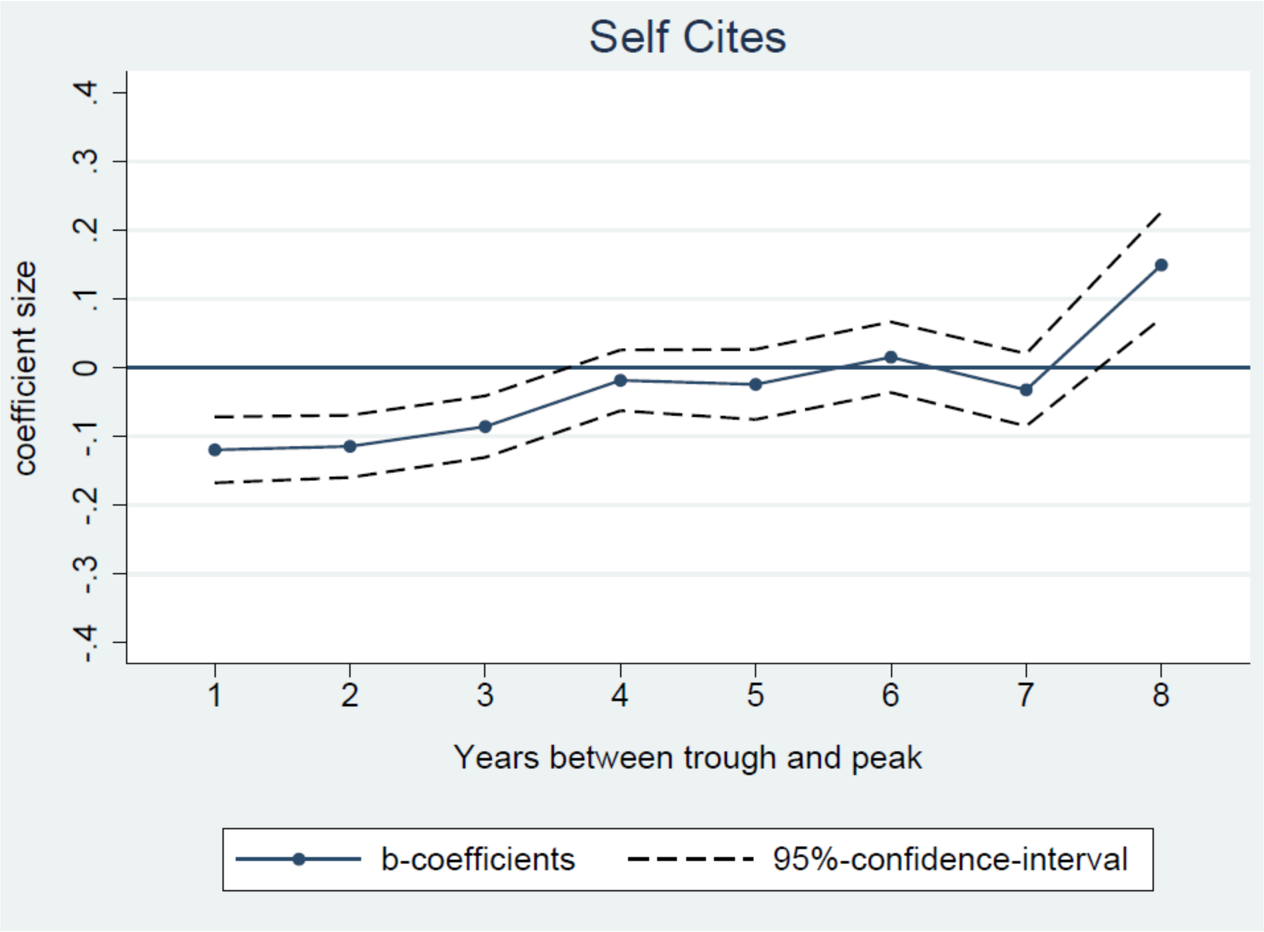
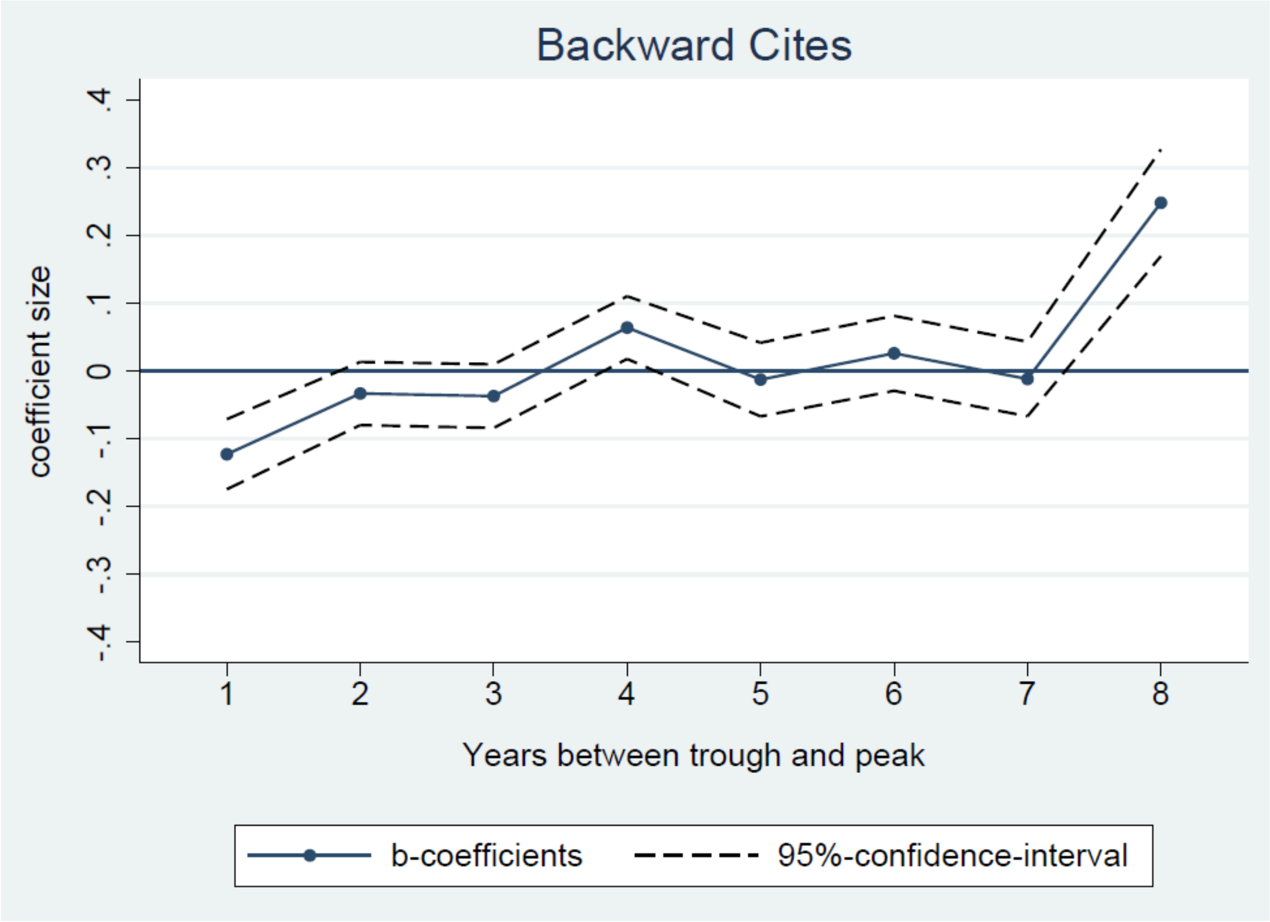
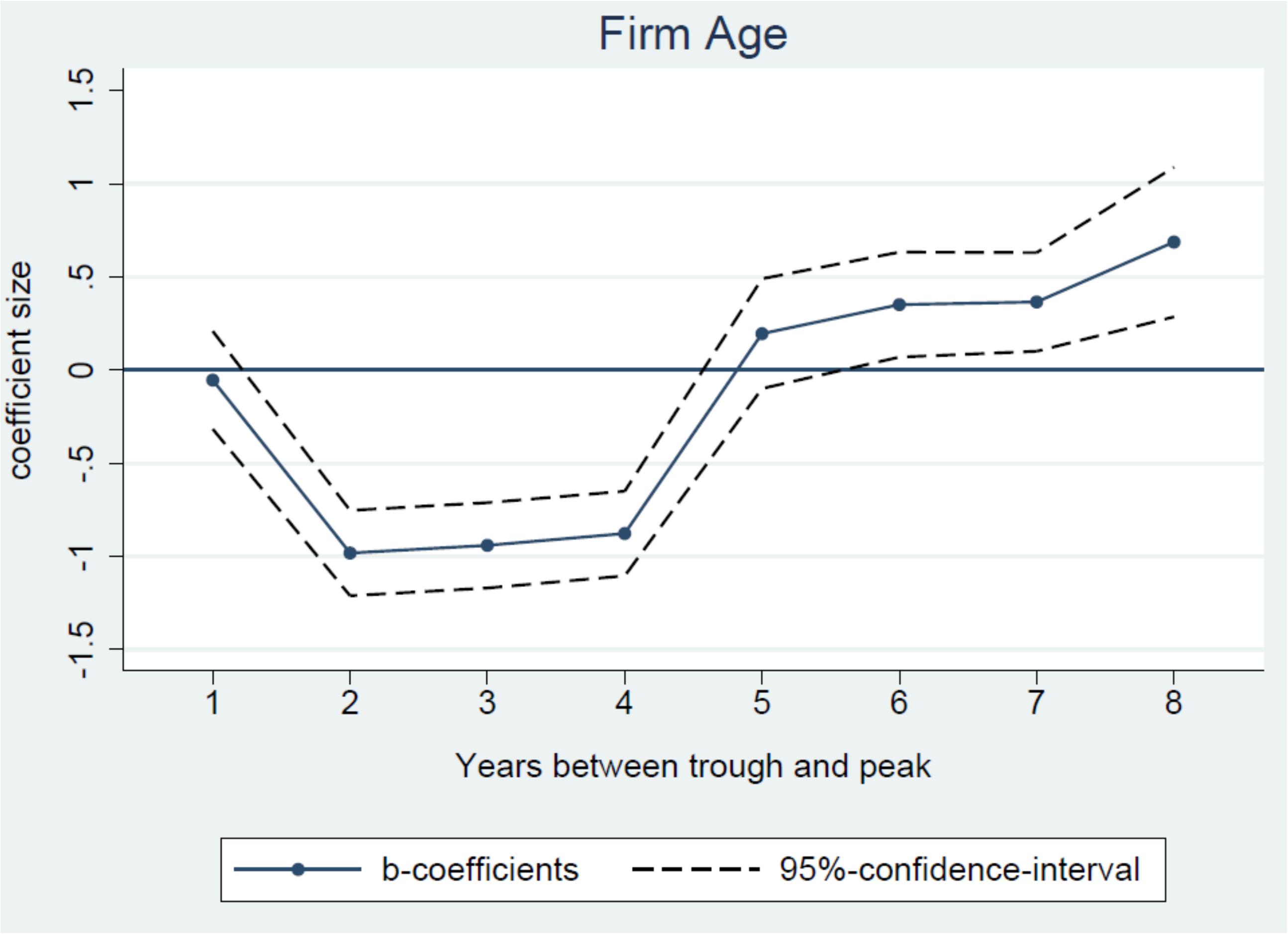


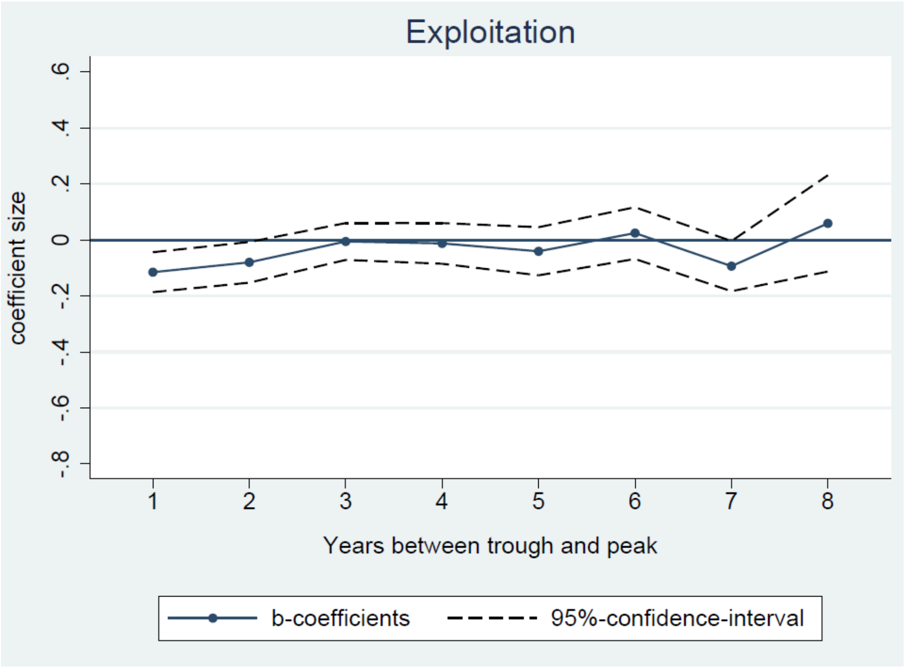
Individual Components over the Business Cycle

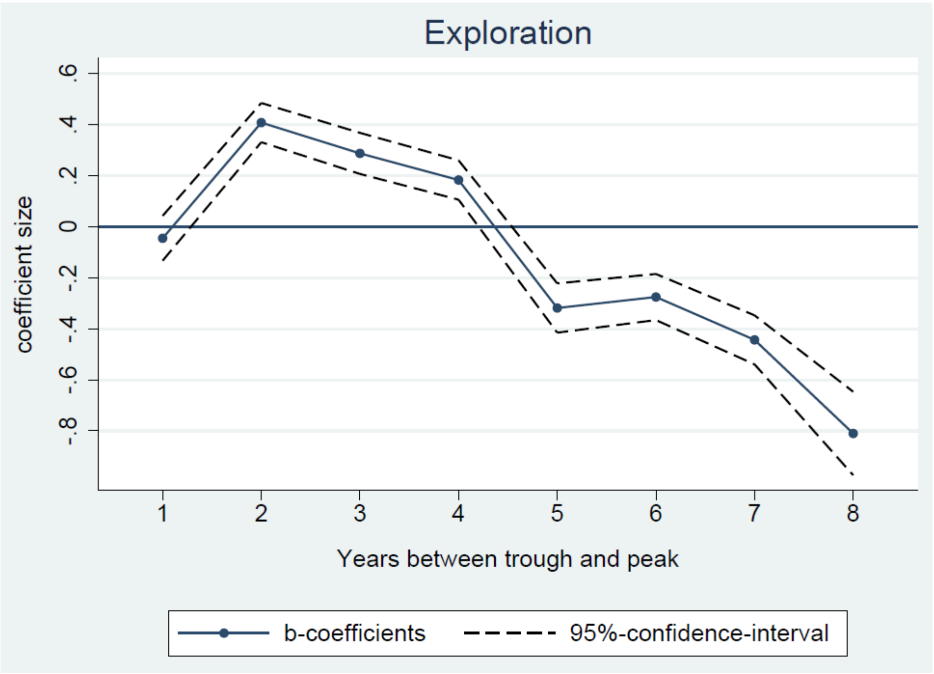


Extensive or Intensive Margins?

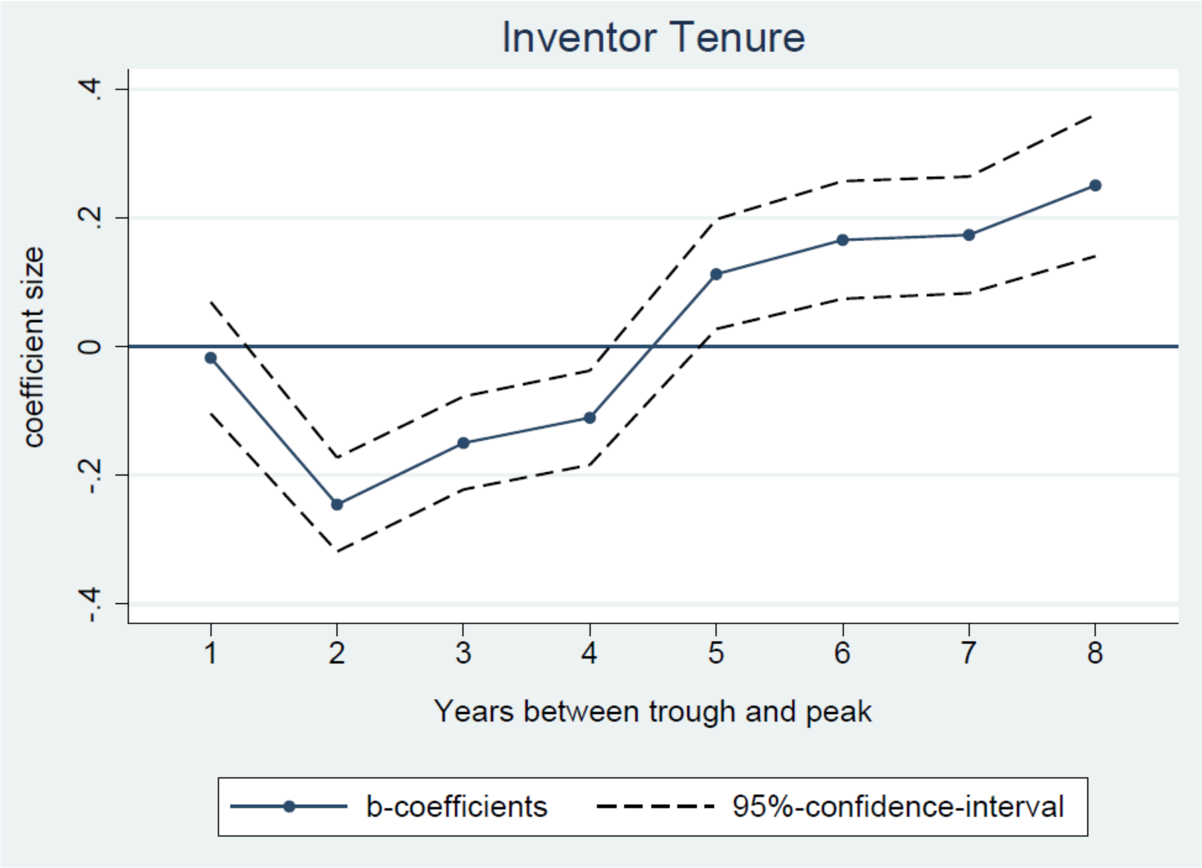


Extensive or Intensive Margins?





Inventor Tenure over the Business Cycle



Relation with GDP Growth

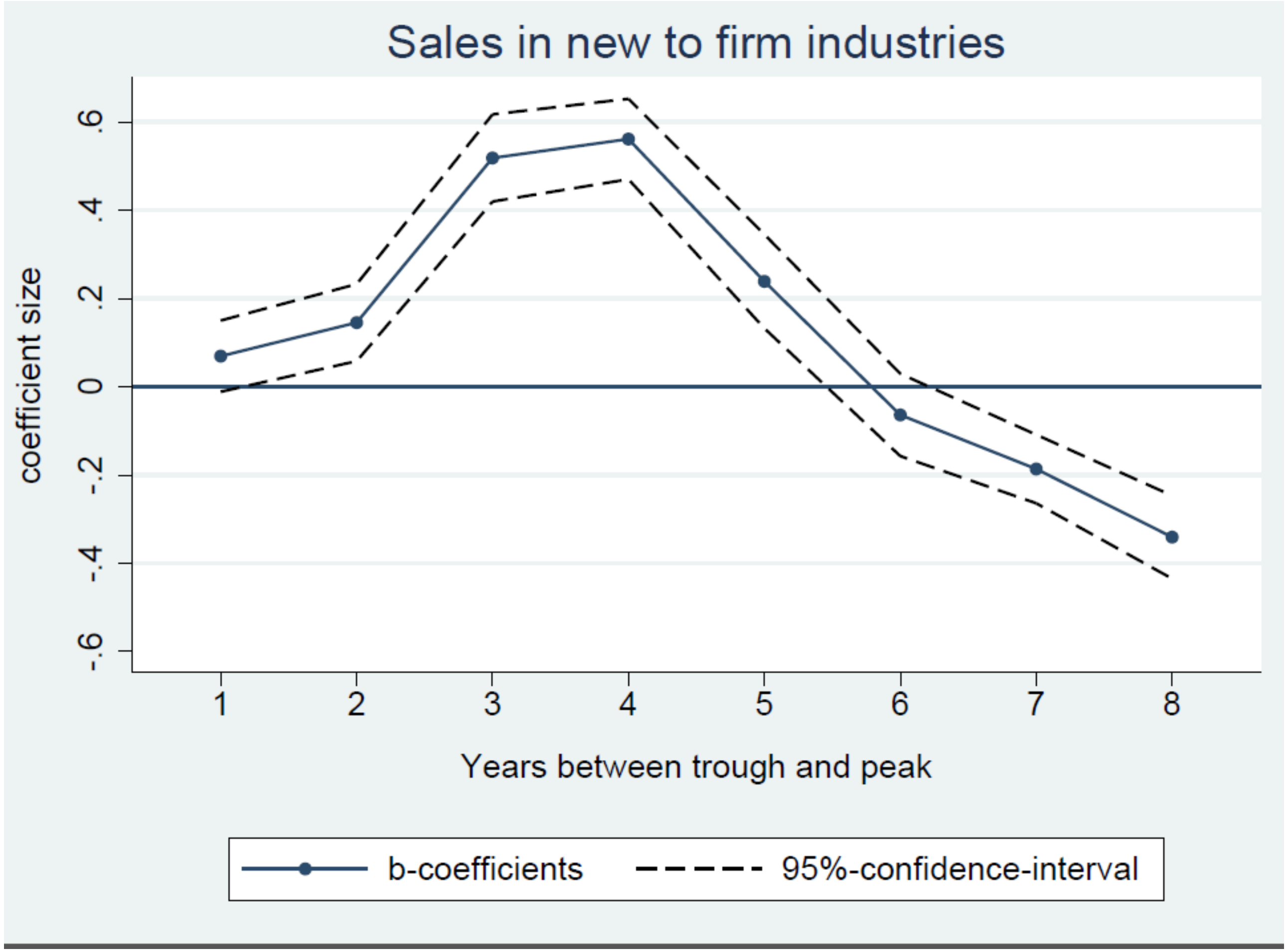
- Explore

	a	b	c
	GDP Growth t+1	GDP Growth t+2	GDP Growth t+3
Explore PCA Score	5.258***	3.733***	3.253***
	(1.061)	(0.825)	(1.024)
N	25	25	25
r2	0.550	0.419	0.357

- Exploit

	a	b	c
	GDP Growth t+1	GDP Growth t+2	GDP Growth t+3
Exploit PCA Score	-4.608***	-3.271***	-2.254**
	(1.142)	(1.073)	(1.056)
N	25	25	25
r2	0.472	0.360	0.191

A Non-Patent Related Measure of Exploration



Summary

- Puzzle: Innovation, as measured by R&D, is procyclical
- Model allowing different types of innovation
  - –Exploration countercyclical; exploitation procyclical
- Metrics of firm level exploration/exploitation
  - – PCA of readily available patent portfolio measures
- Exploration is countercyclical and exploitation is procyclical