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Uncertainty, Risk, and Capital Growth

SAFE Working Paper No. 388 | May 2023

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Electronic copy available at: https://ssrn.com/abstract=4465821

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March 2023

Abstract

We find that high macroeconomic uncertainty is associated with greater accumulation of physical capital, despite a reduction in investment and valuations. To reconcile this puzzling evidence, we show that uncertainty predicts lower depreciation and utilization of existing capital, which dominates the investment slowdown. Motivated by these dynamics, we develop a quantitative production-based model in which firms implement precautionary savings through reducing utilization rather than raising investment. Through this novel intensive-margin mechanism, uncertainty shocks command a quarter of the equity premium in general equilibrium, while flexibility in utilization adjustments helps explain uncertainty risk exposures in the cross-section of industry returns.

JEL Classification: G12, E32, D81, D50

Keywords: Uncertainty, Production, Asset Pricing, Utilization, Depreciation, Equity Premium

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Extensive empirical evidence suggests that high macroeconomic uncertainty coincides with adverse times for the real economy and financial markets. Indeed, an increase in aggregate uncertainty is associated with a business cycle trough and a persistent decline in consumption, investment, and output. At the same time, firm valuations decline while the market risk increases. These findings spurred a large and growing literature which aims to reconcile the dynamic interactions between uncertainty, economic growth, and asset markets.

In this study, we present novel empirical evidence that enriches and challenges the common view on the propagation of uncertainty shocks in capital markets. We document that both in the aggregate time series and across economic sectors, high uncertainty is associated with *greater accumulation* of future capital (as measured by either the BEA or by Compustat), in spite of a decrease in investment. This fundamental result is surprising at a first glance, as typically investment and capital growth are synonymous.

Investment in new capital, however, only governs an extensive margin of capital formation. The intensive margin, due to the time-varying deprecation and utilization of the existing capital, could also respond to uncertainty shocks and reconcile the divergent dynamics of capital and investment. Indeed, we find that investment, utilization, and the capital depreciation rate all decrease following a rise in aggregate economic uncertainty. The decline in depreciation cushions the investment slowdown, and is quantitatively large enough to induce a capital build-up at times of high uncertainty. Consequently, our evidence highlights a rich pattern of propagation of uncertainty shocks in real capital dynamics, which is a novel contribution to the literature.

We next develop and estimate a production-based macro-finance model which incorporates empirically-driven extensive and intensive margins of capital accumulation. The model can explain our novel empirical findings, alongside the existing evidence on uncertainty and economic growth. In addition, we use the model to show that the spill-over of uncertainty shocks from real to financial capital markets yields important implications for aggregate and cross-sectional risk premia.

A key insight of our model is that lowering utilization can substitute higher investment

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for precautionary saving – with the benefit of avoiding any costs of new capital installation. Specifically, a rise in aggregate uncertainty pushes firms to build up capital as a buffer against large downside moves in future productivity. In the model, under-utilization of capital persistently decreases its depreciation rate. As a result, firms substantively lower the utilization rate of the capital already installed, preserving it for future use. Investment, on the other hand, is driven by two opposite forces. A positive uncertainty shock persistently drops utilization, which lowers the expected marginal product of capital. Simultaneously, the same shock decreases the equilibrium risk-free rate. Quantitatively, in our setup, the impact of lower effective productivity dominates. Consequently, aggregate investment declines, while future capital increases, as in the data. Thus, the model can rationalize a surprising build up of capital at times of economic slowdown due to the rise in uncertainty.[1] Lastly, lower utilization also decreases the level of current and future output. The decline in output is larger than the decline in investment, and as a result, consumption decreases as well, resulting in a full business-cycle trough, and an increase in the marginal utility of investors.

Importantly, our utilization-driven channel for explaining capital formation in general, and suppressing investment in particular, following higher uncertainty is novel, and differs from existing mechanisms, such as real options or time-varying markups. It does not require imperfect competition or non-convex adjustment costs, and can be easily incorporated into any Neo-Classical or New-Keynesian framework. Furthermore, existing frameworks either fail to eliminate the precautionary savings effect of uncertainty on investment (ipso-facto, leading to a divergence of investment from consumption), or alternatively, depress both investment and future capital growth in response to high uncertainty, contrary to the data.[2]

While our framework does not directly target asset-price data, it is able to capture salient

[1]This divergence of investment and capital growth only occurs with respect to second-moment productivity shocks. Negative first-moment productivity shocks lower both investment and capital, so that capital and investment are procyclical, in both the data and our model.

[2]To help further assess the contribution of our mechanism vis-à-vis existing channels, we extend our baseline model, and incorporate flexible utilization and persistent depreciation dynamics into a New-Keynesian model featuring nominal price rigidity. We show that depending on the dynamics of aggregate productivity, our mechanism is either *necessary* to induce a drop in investment following a rise in uncertainty, or at the very least, substantially *amplifies* the adverse effect of higher uncertainty on real variables above and beyond the countercyclical markup channel.

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features of the aggregate and sectoral asset valuations. With early resolution of uncertainty, uncertainty shocks increase the marginal utility, and thus bear a negative price of risk. Further, the firm's investment rate and stock prices comove, a standard implication of q-theory. Because high uncertainty decreases investment, through our mechanism that depends on flexible utilization, equity price exposure to uncertainty risks is negative. Coupled with a negative market price of risk, uncertainty shocks thus contribute positively to the model-implied equity premium, and account for about a quarter of its magnitude. In contrast, when utilization rate is constant, high uncertainty increases investment and firm valuations. Counterfactually, equities become hedges of uncertainty fluctuations, and demand less than a third of the original risk compensation.

In addition to the aggregate risk premium, the model delivers specific cross-sectional predictions for the relation between the uncertainty exposures of firms' returns and their capital utilization rates. In particular, firms whose utilization is more volatile or more sensitive to aggregate uncertainty fluctuations should have their valuations be more exposed to uncertainty risk. Thus, the flexibility of adjusting the utilization rate helps to microfound the observed exposures of stock returns to uncertainty shocks. We assess and corroborate these model implications using the cross-sectional data on manufacturing and utility industries.

Lastly, our model mechanism relies on persistent fluctuations in the depreciation rate. While a contemporaneous connection between depreciation and utilization is a common ingredient in New-Keynesian models, in our specification utilization has a long-lasting effect on future depreciation. This turns the intensive margin of utilization into a quantitatively relevant vehicle for intertemporal capital allocation, and in an asset-pricing context, endogenously induces low-frequency variations in the expected consumption growth (akin long-run risks). We show that the data are far more consistent with depreciation being more persistent than utilization, rather than the two sharing the same autocorrelation as in typical specifications in the literature. We further offer potential economic explanations for the dynamic link between utilization and depreciation, including reallocation of capital across

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sectors, or heterogeneity in depreciation rates across different types of capital.[3] [4]

Related literature. The theoretical literature on the impact of uncertainty shocks primarily focuses on the negative relation between uncertainty and investment. The studies of McDonald and Siegel (1986) and recently Bloom, Bond, and Van Reenen (2007), Bloom (2009) and Alfaro, Bloom, and Lin (2018) use a real option channel (or "bad news" principle) to explain why uncertainty suppresses investment. Importantly, the positive effect of uncertainty on capital stock which we focus on in this study differs from the investment overshoot effect in real option models. In a real option model, future capital growth increases because of a simultaneous overshoot in investment. In our model, capital rises while the *contemporaneous* investment declines, leading to divergence between the two.

A number of recent studies have confirmed, empirically and theoretically, that high uncertainty increases firms' cost of capital, making investment more costly (see, e.g., Christiano, Motto, and Rostagno, 2010; Gilchrist, Sim, and Zakrajšek, 2014; Arellano, Bai, and Kehoe, 2019; Bretscher, Hsu, Tamoni, et al., 2019, or Fernández-Villaverde, Guerrón-Quintana, Rubio-Ramirez, and Uribe, 2011 in the context of an open economy). Di Tella and Hall (2021) feature uninsurable idiosyncratic risk which creates a time-varying risk premium wedge that suppresses investment and hiring. We differ from these studies in two ways. First, in all of the aforementioned papers depreciation rate is constant. Thus, they cannot account for our new evidence on the response of depreciation rate to uncertainty shock, and for the divergence between investment and capital growth following higher uncertainty. Second, in all these studies with an exception of Di Tella and Hall (2021), uncertainty de-

[3]As a conceptual example, inventory capital depreciates faster than equipment. If firms halt production and new input orders at times of elevated uncertainty, and sell from their inventory, utilization decreases. Simultaneously, the relative weight of inventory goods decreases while that of fixed assets rises – both contemporaneously and in the future, since these weights depend on stock variables. Consequently, the overall depreciation rate would feature a sizable persistent decline, consistent with our modeling dynamics and the BEA data (see more details in Section 2.1).

[4]As a practical example, Fedex experienced a sharp decline in utilization during the inception of COVID. In its 2020 10-K filing it states *"Our business is capital intensive, with approximately 56% of our owned assets invested in our transportation... Because we utilize many of our capital assets over relatively long periods... we periodically evaluate adjustments to our estimated service lives...This evaluation result in changes in the estimated lives and residual values used to depreciate our aircraft and other equipment (p.86)."*

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creases investment but does not generate positive contemporaneous comovement between consumption and investment.

Fernández-Villaverde, Guerrón-Quintana, Kuester, and Rubio-Ramírez (2015) and Basu and Bundick (2017) rely on a New Keynesian framework with monopolistic competition and sticky prices to generate a drop in consumption and investment in response to uncertainty shocks. Both studies feature flexible utilization; however, as in the other New Keynesian models, utilization only impacts the contemporaneous depreciation rate, and mainly serves to extend the duration of price stickiness. Without our channel of added persistence in depreciation, the existing models cannot fully account for our novel empirical evidence.[5]

Our paper further contributes to the production-based asset-pricing literature.[6] In a standard production setting, uncertainty shocks lower the equity premium and increase stock prices, in contrast to the endowment economies and the data.[7] We show that in our model, uncertainty shocks decrease stock prices, increase the marginal utility, and contribute positively to the market risk premium. Thus, our channel complements other production-based approaches in which discount rate shocks suppress investment and raise equity premium, such as resource reallocation (e.g., Gao, Hitzemann, Shaliastovich, and Xu, 2016, Bansal, Croce, Liao, and Rosen, 2019, Basu, Candian, Chahrour, and Valchev, 2021), endogenous growth (e.g., Kung and Schmid, 2015), uninsurable idiosyncratic risk (e.g., Dou, 2017, Herskovic, Kelly, Lustig, and Van Nieuwerburgh, 2016), debt overhang (e.g., Chang, d'Avernas, and Eisfeldt, 2021), or multiple sectors and uncertainties (e.g., Segal, Shaliastovich, and Yaron, 2015; Segal, 2019). Our paper also related to studies that incorporate flexible utilization in asset pricing (see, e.g., Garlappi and Song, 2017; Grigoris and Segal, 2022; Ai, Li, and Tong, 2021). These studies do not consider the interaction between utilization and second-moment shocks.

[5]Under the parameters of Basu and Bundick (2017), the investment decline following an uncertainty shock dominates the drop in utilization and depreciation, so that future capital growth falls, in contrast to our empirical evidence (see Figure OA.1.4 in the Online Appendix).

[6]See, e.g., Berk, Green, and Naik 1999; Boldrin, Christiano, and Fisher 2001; Zhang 2005; Wu, Zhang, and Zhang 2010; İmrohoroğlu and Tüzel 2014; Favilukis and Lin 2016; Belo, Li, Lin, and Zhao 2017.

[7]See, e.g., Bansal and Yaron, 2004; Boguth and Kuehn, 2013; Buraschi, Trojani, and Vedolin, 2014; Johannes, Lochstoer, and Mou, 2016; Ai and Kiku, 2016, among many others

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Finally, a recent strand of the empirical literature aims to assess and quantify the causal nature of uncertainty shocks on the economic fundamentals. In particular, Berger, Dew-Becker, and Giglio (2020) and Ludvigson, Ma, and Ng (2021) question the role of macroeconomic uncertainty to induce recessions. Our findings that uncertainty has a negative effect on investment while positive on the future stock of capital can potentially shed light on the ambiguous role of macro uncertainty for aggregate economic indices and prices.

The rest of the paper is organized as follows. We establish our novel empirical evidence in Section 1. Section 2 describes the model setup and the estimation. In Section 3 we discuss model implications for macro dynamics, while Section 4 shows the role of uncertainty shocks for financial capital markets. In Section 5 we test key predictions of the model using real quantities and asset prices. We provide concluding remarks in Section 6.

1 Empirical evidence

In this section we provide our key empirical evidence on the relation between macro uncertainty and the components of capital accumulation. We establish that an increase in uncertainty is associated with a lower depreciation rate and higher future capital growth, in spite of lower investment rates. While the evidence pertains to real capital markets, it impacts valuations in financial capital markets, as we will show through the lens of the subsequent model.

1.1 Data

We obtain data on industrial production, capacity utilization, and inflation from the Federal Reserve Bank of St. Louis. Utilization-adjusted Total Factor Productivity (TFP) measure of Fernald (2014) comes from the San Francisco Fed. Real consumption, defined as personal consumption expenditures on non-durables and services, is from the Bureau of Economic Analysis (BEA). The BEA Fixed Assets Accounts further provide data on quantity indices for the net stock, economic depreciation, and investment in private non-residential fixed assets. All fixed asset indices are chained to the year 2012. We convert the

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indices to real dollars by multiplying them by their respective dollar amount as of 2012. The depreciation and investment rates are constructed as the dollar depreciation and investment amounts in year t, respectively, divided by the stock of capital in year $t-1$.

Capital stock and investment measures are routinely used in the macroeconomic research to define economic ratios of interest (investment-to-capital or output-to-capital ratios) or in TFP computations (Fernald, 2014). While it is less common to separately consider fluctuations in the depreciation rate, it is important to highlight that capital stock, investment, and depreciation estimates are directly related to each through the capital accumulation equation, which is satisfied under the BEA measurement period-by-period. Thus, the three measures are on par in terms of their economic and empirical applicability. We also provide robustness checks using alternative measures of capital and depreciation from accounting statements in Section 1.4.

Finally, we obtain asset-price data from CRSP. We measure the nominal risk free rate as the 3-month T-bill yield, and the market return by the value-weighted market index return. Based on the availability of productivity and fixed assets data, all variables are measured at an annual frequency from 1948 to 2018, with an exception of capacity utilization data which are only available from 1968.

1.2 Measuring macroeconomic uncertainty

Uncertainty has many facets, each having potentially different implications for the macroeconomy.[8] In this study, we use the term "macro uncertainty" to refer to a broad, aggregate uncertainty pertaining to the supply (production) side of the economy. From an economic perspective, fluctuations in supply-side uncertainty affect the stochastic volatility of permanent productivity shocks, and consequently, induce a sizeable and persistent impact on production allocations, consumption decisions, and the marginal utility of economic agents.[9]

[8] An incomplete list includes: financial uncertainty (VIX), real uncertainty (Jurado, Ludvigson, and Ng, 2015), demand uncertainty (Basu and Bundick, 2017; Bianchi, Kung, and Tirskikh, 2022), policy uncertainty (Baker, Bloom, and Davis, 2016), fiscal uncertainty (Fernández-Villaverde et al., 2015), idiosyncratic uncertainty (Herskovic et al., 2016), interest rate uncertainty (Bretscher, Schmid, and Vedolin, 2018).

[9] In contrast, firm-level uncertainty, while sizeable, does not constitute a systematic source of risk in complete markets. Similarly, facets of aggregate demand-side uncertainty typically govern the volatility of

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As such, in the benchmark specification we construct an intuitive measure of macroeconomic uncertainty based directly on production time-series, which ensures a tight connection between the data and the model. Other popular measures of aggregate uncertainty, such uncertainty indices of Jurado et al. (2015) (henceforth, JLN) or economic policy uncertainty of Baker et al. (2016) (henceforth, EPU) are less suited for our empirical analysis. Indeed, the JLN macro uncertainty captures the common component of uncertainty across a variety of economic indicators, from both the supply and demand sides, many of which are outside of the model. Likewise, the fluctuations in policy uncertainty captured by the EPU index are conceptually distinct from the production uncertainty we are interested in. Nonetheless, in Section 1.4 we verify the robustness of our key findings to JLN or EPU measures.

Our macroeconomic uncertainty, denoted by v_t, is aimed to capture the predictable variation in a macroeconomic production growth variable of interest y, that is, $v_t = Var_t(\Delta y_{t+1})$. In the benchmark analysis, we construct v_t following a predictive approach similar to Bansal, Khatchatrian, and Yaron (2005) and Segal et al. (2015). First, we estimate an AR(1) model using the highest-frequency time-series available for the growth variable of interest y_t, and use the residuals of this regression, denoted by $\varepsilon_{y,t+1}$, as innovations to macroeconomic growth. Second, we define the realized variance of y_t, denoted by RV_t, as follows:

$$RV_{t+1} = \sum_{i=1}^{N} \varepsilon^2_{y,t+\frac{i}{N}}, \tag{1}$$

where N represents the number of observations of y_t available during one period (a one year in our case). The realized variance is a backward-looking measure of the variation in the underlying variable y_t. Consequently, in the third step we use the predictable component of this measure to proxy for ex-ante macroeconomic uncertainty v_t. Specifically, we project the logarithm of time $t+1$ realized variance on a set of time t predictors, Γ_t:

$$\log\left(RV_{t+1}\right) = \nu_0 + \nu'\Gamma_t + \varepsilon_{rv,t+1}, \tag{2}$$

and set the ex-ante macro uncertainty to the exponentiated fitted value of projection (2):

$$v_t = \exp\left(\nu_0 + \nu'\Gamma_t\right). \tag{3}$$

mean-reverting shocks to preferences, taxation, or sentiments. Such transitory shocks play a limited role for the aggregate risk premium as well (see, e.g., Alvarez and Jermann, 2005).

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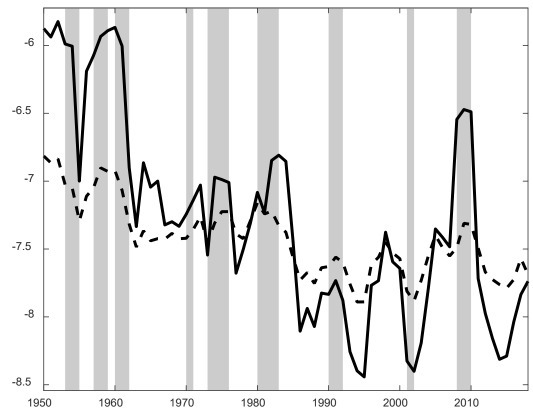
Figure 1: **Realized and ex-ante macroeconomic uncertainty**



The figure shows the time series of log realized variance of industrial production (solid line) and log of the ex-ante macro uncertainty (dashed line). Both series are smoothed over the past three years. The shaded areas represent NBER recessions.

The log transformation ensures that our ex-ante uncertainty measures is strictly positive.[10]

In the benchmark implementation, we let y_t be the industrial production index. We use monthly frequency observations to construct its realized variance at an annual frequency, so that $N = 12$.[11] The benchmark predictors Γ_t include the log of the realized variance, $\log(RV_t)$, the nominal risk free rate, $r_{f,t}$, the market return, $r_{m,t}$, the rate of inflation, π_t, and utilization-adjusted TFP growth, ΔTFP_t.

Figure 1 shows (the log of) the realized volatility of industrial production RV_t, and the ex-ante macro uncertainty v_t. For the purpose of illustrating the cyclical properties, both time series are smoothed over the last 3 years to reduce high frequency oscillations. The ex-ante macro volatility is more persistent and less volatile compared to the realized variance. Both uncertainty measures are countercyclical, typically rising during the NBER recessions. Consistent with Stock and Watson (2002), macro uncertainty shows a persistent moderation. Nonetheless, an Augmented Dickey-Fuller test rejects the unit root null at the 10% level. [12]

[10]We obtain very similar results when the left-hand side of projection 2 is simply RV_{t+1}, and v_t is the fitted value of the projection.

[11]Neither TFP nor consumption nor GDP are available at a sufficiently high frequency.

[12]Similarly, Campbell, Lettau, Malkiel, and Xu (2001), use statistical tests to confirm that aggregate

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1.3 Macro uncertainty and capital accumulation

In this section we examine the relation between macroeconomic uncertainty and key determinants of capital accumulation. We establish several novel findings:

(1) high uncertainty is associated with lower depreciation and utilization of existing capital;

(2) high uncertainty is associated with an increase in the growth of the future capital stock.

Consistent with existing studies, we further show that high uncertainty is associated with a decrease in the growth of investment rate. To tie all the evidence together, we argue that capital utilization and depreciation both drop following episodes of high uncertainty. While investment decreases as well, quantitatively, the reduction in investment is weaker than a drop in the depreciation rate. This finding helps explain why the capital stock can increase in the future following higher uncertainty, despite a drop in investment.

Correlations. We start the analysis with plain correlations. Table 1 shows contemporaneous correlations of each variable of interest Δy with macro uncertainty v. The variables of interest are private nonresidential investment rate I/K, nonresidential depreciation rate δ, the stock of nonresidential capital K, and capacity utilization u. To ensure stationarity, we use annual log growth rates for these variables in the empirical analysis.[13] The Table shows that macroeconomic uncertainty has a negative correlation with the growth of δ, I/K, and u. This is generally consistent with a common view that macroeconomic uncertainty causes and/or deepens recessions. More surprisingly, the correlation between v_t and the growth of the capital stock K is positive.

To ensure that the correlation evidence is not driven by our specific methodology of constructing the ex-ante uncertainty v_t, in Table 1 we also report the correlations between the

volatility has no significant trend using monthly data from 1926 to 1997. Despite the above, we ensure that the results to follow are not driven by any *qualitative* moderation: (i) we show in Online Appendix Table OA.1.1)(Panel C) that the key findings are robust to a time-trend inclusion; (ii) in Tables 3 and 4 we show that the findings hold in the second half of the sample, in which macro uncertainty does not exhibit a qualitative trend.

[13] While the stock of capital, K_t, is clearly non-stationary, several studies have pointed out that investment in fixed assets ratio, I/K, features a secular downward trend over the past 30 years (see, e.g., Gutiérrez and Philippon (2016)), whereas the depreciation rate, δ, exhibits an upward trend.

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Table 1: **Uncertainty and capital accumulation: Correlations**

y	$Corr(\Delta y, v)$	$Corr(\Delta y, RV)$	$Corr(\Delta y, g)$
I/K	-0.27	-0.19	0.51
δ	-0.27	-0.26	0.27
K	0.17	0.08	0.49
u	-0.30	-0.51	0.44

The table shows pairwise correlations of economic variables with ex-ante macroeconomic uncertainty, v, realized macroeconomic uncertainty, RV, and level of economic growth, g. The variables of interest y are the stock of nonresidential capital, K, private nonresidential investment rate, I/K, nonresidential depreciation rate, δ, and capacity utilization, u. v and RV correspond to the ex-ante and realized variation in industrial production growth, respectively, and g is the real consumption growth. Annual data on stock, investment rate, and depreciation rate are from 1948 to 2018. Annual data on utilization rate are from 1967 to 2018.

growth rate in the aforementioned variables and the realized variance of industrial production, RV_t. All correlations maintain the same sign. In particular, the correlation between the realized variance and capital growth remains positive. The correlation between the realized variance and the growth in depreciation is more negative than the correlation between the realized variance and investment growth (-0.26 vs -0.19, respectively).

Regression Evidence. Economic models, including the one in Section 2, feature shocks to the first-moments (g_t) in addition to the second-moments (v_t) of the macroeconomic growth. To be consistent with the theory, we need to consider the relation between the uncertainty, v_t, and the variables of interest, controlling for the first-moment macro growth, g_t. In the benchmark implementation, we use log consumption growth, $g_t = \Delta c_t$, as the first-moment control. Consistent with the literature, Table 1 shows that the growth rates in I/K, δ, K, and u are procyclical, and have a positive correlation with g_t.[14]

To document the dynamic impact of uncertainty controlling for the first-moment shocks, we regress the growth rate for variable y between year $t-1$ and year $t+H-1$ on the current

[14] In Subsection 1.4, we consider the robustness of our main results to alternative methodologies of measuring v in the data and to other proxies of g (e.g., log TFP growth). We also consider robustness using the Jurado et al. (2015) macro uncertainty measure. Indeed, the correlation between v and JLN is approximately 40%.

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Table 2: **Uncertainty and capital accumulation: Regression evidence**

Horizon H	β_v	t-stat	β_g	t-stat
y = Private nonresidendtial investment rate				
1 years	-0.22	[-2.14]	0.49	[4.64]
2 years	-0.18	[-1.61]	0.50	[4.51]
3 years	-0.20	[-1.62]	0.29	[2.36]
y = Private nonresidendtial depreciation rate				
1 years	-0.24	[-1.78]	0.24	[1.90]
2 years	-0.31	[-1.98]	0.27	[2.35]
3 years	-0.34	[-2.27]	0.19	[1.75]
y = Private nonresidendtial capital				
1 years	0.23	[2.35]	0.52	[4.01]
2 years	0.24	[2.60]	0.63	[5.03]
3 years	0.25	[2.37]	0.63	[4.74]
y = Capacity utilization rate				
1 years	-0.26	[-2.27]	0.42	[2.84]
2 years	-0.42	[-4.07]	0.14	[0.99]
3 years	-0.44	[-4.46]	-0.06	[-0.41]

The table shows the results of the regression: $\frac{1}{H}\Delta y_{t-1\to t+H-1} = const + \beta_{v,H}v_t + \beta_{g,H}g_t + error$. v is macro uncertainty, measured by the ex-ante volatility of industrial production. g is the real consumption growth. The variables of interest y are the stock of nonresidential capital, private nonresidential investment rate, nonresidential depreciation rate, and capacity utilization. Annual data on stock, investment rate, and depreciation rate are from 1948 to 2018. Annual data on utilization rate are from 1967 to 2018. Standard errors are robust and Newey West adjusted. All variables are standardized.

first- and second- moments of macroeconomic growth:[15]

$$\frac{1}{H}\Delta y_{t-1\to t+H-1} = const + \beta_{v,H}v_t + \beta_{g,H}g_t + error, \tag{4}$$

where $\Delta y_{t-1\to t+H-1} = \sum_{h=1}^{H} \Delta y_{t-1+h}$. When $H = 1$, the slope coefficients capture the partial contemporaneous correlations of the left-hand side variable with uncertainty and real growth, while for $H > 1$ they measure the cumulative immediate and future effects up to horizon $H - 1$. We set $H \in \{1, 2, 3\}$. For ease of interpretation, we standardize both the dependent and independent variables.

The slope coefficients and their Newey-West t-statistics for the growth in investment, depreciation, utilization, and capital stock are documented in Table 2. Consistent with the

[15] In Online Appendix Table OA.1.1 we repeat projection (4), but replace the level of macro uncertainty v_t, by its shock $\epsilon_{v,t}$. The results are qualitatively and quantitatively similar.

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correlation evidence in Table 1, Table 2 shows that the slope coefficient on g_t is positive and statistically significant in nearly all of the cases. At the same time, the slope coefficient β_v is negative for the growth rates in investment, depreciation, and capacity utilization, and positive for capital stock. The estimated effects are statistically and economically significant: a one standard deviation increase in uncertainty leads to about a quarter to a half standard deviation change in the variables of interest, and the responses get magnified at longer horizons.

The described effects of uncertainty are quite striking as they present a challenge for the existing literature. How can the capital stock grow when investment falls at times of high uncertainty? To satisfy the capital accumulation equation, the only available margin is the change in capital depreciation. Indeed, the regressions results show that depreciation rates significantly drop at times of high uncertainty. Quantitatively, the depreciation decrease is large enough to compensate for the drop in investment and save capital for the future; as a suggestive evidence, the slope coefficients are larger, in absolute value, for depreciation than for investment ($\beta_{v,H,y=\delta} < \beta_{v,H,y=I/K} < 0$).

Finally, it is important to contrast our novel findings to some well-established channels connecting uncertainty and capital. First, one can conjecture that mean reversion (recovery) could account for a positive capital growth following an uncertainty shock. However, we deliberately measure the cumulative capital growth starting at time $t-1$ onward (as opposed to time t), such that the slope coefficient on uncertainty captures the change in the stock of capital relative to its value *before* the uncertainty shock realizes. Second, Bloom (2009) documents that uncertainty shocks lead to an investment overshoot in the long-run. In Bloom (2009), however, capital growth increases because future investment rises (i.e., ΔK and I/K *comove*); while in our empirical findings, as well as in the subsequent model, the capital stock increases despite of a simultaneous investment slowdown (i.e., ΔK and I/K *diverge*). The Oi-Hartman-Abel effect can similarly induce an expansion in the capital stock, but also predicts a counterfactual comovement between capital growth and investment following second-moment shocks.[16] Consequently, we formalize a novel channel to reconcile

[16]Another plausible hypothesis is that the observed increase in the capital stock following higher uncer-

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the evidence in Section 2.

Impulse Responses. To further illustrate the impact of macro uncertainty on capital accumulation, Figure 2 provides impulse responses of capital-related measures to macro uncertainty shocks. These are computed from Smooth Local Projection (SLP) (Barnichon and Brownlees, 2019), which extends the Local Projection methodology of Jordà (2005). In robustness section 1.4 we change the methodology to Cholesky decomposition.

Specifically, let Y_t be the vector $[g_t, v_t, \Delta\delta_t, \Delta I/K_t, \Delta K_t]'$. The impulse response functions in panels (a) – (c) of Figure 2 are derived from a full-sample SLP estimation of:

$$\Delta y_{t+H} = \alpha_{(H)} + \beta_{(H)} v_t + \gamma(H)'\omega_t + u_{(H)t+h}, \tag{5}$$

where y is the variable of interest, and $\omega_t = [g_t, \Delta\delta_t, \Delta I/K_t, Y_{t-1}, Y_{t-2}, Y_{t-3}]$. This is equivalent to a vector autoregressive system of the fourth order. The coefficient $\beta(H)$ is approximated using a linear B-splines basis function expansion in the forecast horizon h. The SLP specified in Equation 5 excludes the utilization rate because it is only available from 1967 onward. In panel (d) of Figure 2 we append the vector Y_t and the vector ω_t with Δu_t, and estimate the SLP when y equals to utilization using data from 1967 to 2018.

Panels (a) and (b) of the Figure show that the growth in investment and depreciation rates both fall following an increase in macro uncertainty. However, the impact of uncertainty on depreciation is much more pronounced: one year after the uncertainty shock, the magnitude of depreciation growth's impulse response is twice as large as the investment rate's impulse response. The negative effect of uncertainty on the growth in depreciation persists over the next 15 years. The larger impact of uncertainty on depreciation relative to investment is consistent with the regression evidence in Table 2, and helps explain a positive and significant increase in future capital growth (panel (c)). Lastly, an uncertainty shock lowers capacity utilization's growth rate up to 8 years after.

tainty is driven by an increase in the relative price of investment goods, P_i, rather than an increase in the amount of equipment. Yet, the same logic would counter-factually suggest that investment expenditures should also increase following higher uncertainty, since they are scaled by the same price deflator in the data. Thus, relative price fluctuations cannot reconcile a contemporaneous divergence between investment and capital.

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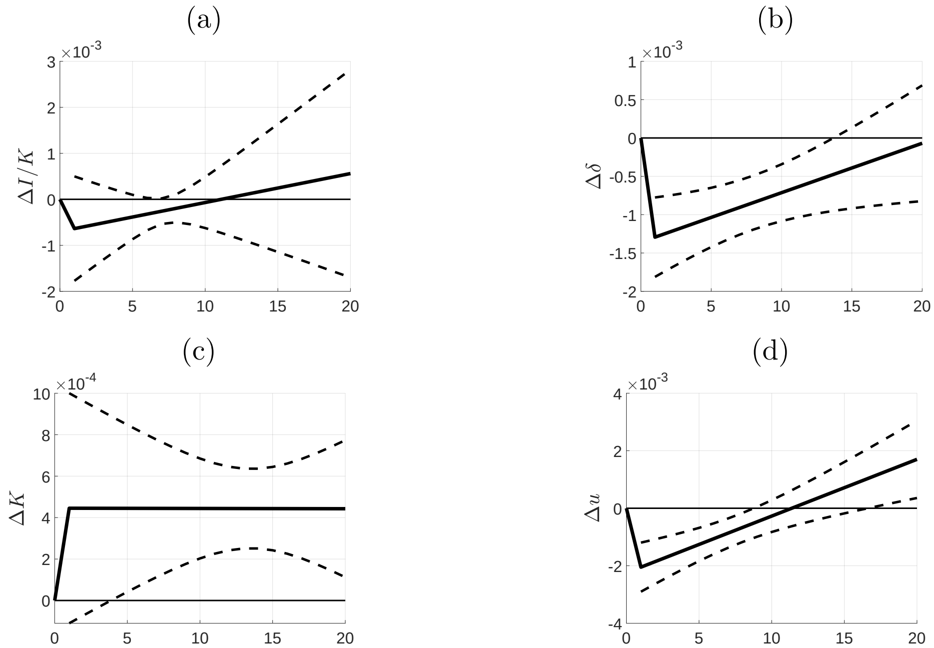
Figure 2: **Uncertainty shocks IRF: Benchmark**



The figure shows the impulse responses of the growth rate of (a) investment rate $\Delta I/K$, (b) depreciation rate $\Delta\delta$, (c) capital stock ΔK, and (d) utilization rate Δu, to uncertainty shocks. The impulse response functions are derived from smooth local projection of Barnichon and Brownlees (2019), and are approximated using a linear B-splines basis function expansion in the forecast horizon H. The dashed lines represent the 90% confidence interval. Panels (a) – (c) are based on a postwar sample from 1948 to 2018. In panel (d) we estimate the smooth local projection for utilization growth using data from the 1967-2018 sample.

1.4 Robustness and extensions

We consider several extensions and robustness checks to support our main findings. We first confirm our main findings using alternative capital measures from accounting statements. We then examine the cross-sectional relationship between average uncertainty and capital growth across industries and at the micro-level. Then, we extend the benchmark evidence to incorporate additional controls, alternative sample periods, measures of first and second moment shocks, and construction of the impulse responses through Cholesky decomposition.

Alternative capital measure. Our baseline results are based on the capital stock and depreciation data from the BEA Fixed Assets Accounts. For robustness, we consider alternative

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measures corresponding to the Property, Plant and Equipment, $PPENT$, for capital, and depreciation DEP net of amortization of intangibles AM, as a fraction of capital $PPENT$, for depreciation. These items are available on firms' accounting statements at Compustat.

Admittedly, capital and depreciation from Compustat reflect accounting practices, and are thus imperfect proxies for the economic measures. At the same time, accounting codes do allow firms to adjust depreciation rates based on their capital utilization. Broadly, Accounting Standard Codification 360 permits firms to select *"methods of apportioning depreciation cost...[to be] based on activity"*, which promotes a continuous connection of utilization and depreciation. Accounting Standard Codification 250 of US GAAP specifically states that *"changes in accounting estimates result from new information...items for which estimate [changes are] necessary are uncollectible receivables, service lives and salvage values."* Similar provisions are available in the IFRS standard.[17]

To corroborate our BEA-based evidence, we regress future cumulative changes in capital and depreciation from Compustat on macroeconomic uncertainty and economic growth, as in equation 4. As shown in Panel G of Tables 3 and 4, an increase in macro uncertainty increases the growth of total capital, and the economic magnitude is even larger than using the benchmark measures of capital in Table 2. Likewise, high macro uncertainty is associated with a persistent and significant decline in Compustat-based total depreciation rate.

Cross-sectional evidence. Our time-series evidence suggests that high aggregate uncertainty is associated with an increase in future stock of capital. To lend further support to this finding, we demonstrate that this positive relation also holds at a dis-aggregated level, and using an alternative measure for the capital stock. Specifically, we collect industry-level data on capital stock and utilization rates. We use the average growth in the book value of firms' total fixed assets ($PPENT$), within an industry, to proxy for capital growth. We also rely on the FRB's report on Industrial Production and Capacity Utilization (report G.17) which provides estimates of capacity utilization for durable producers, nondurable producers, mining and utilities. Our total cross-section encompasses 37 industries which have

[17]Grigoris and Segal (2022) provide further direct evidence that Compustat-based depreciation and utilization comove positively in the cross-section of industries.

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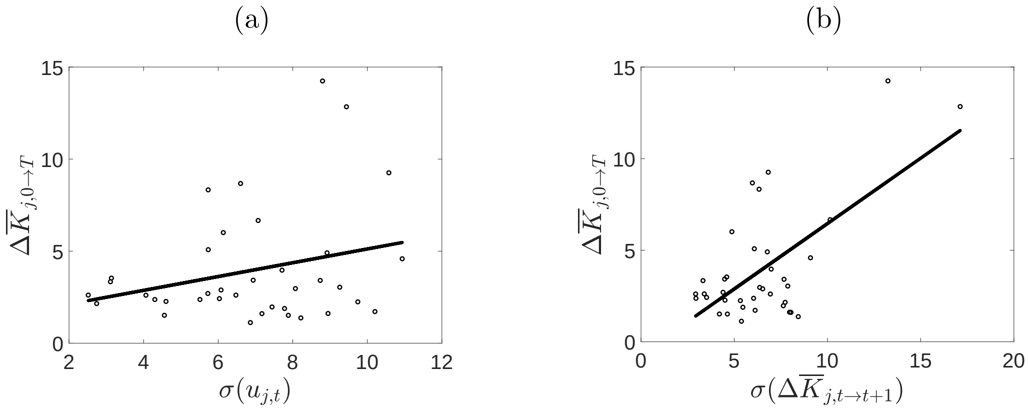
Figure 3: **Volatility and capital growth: cross-section**



The Figure shows a scatter plot of the unconditional mean of capital growth, averaged across all firms in industry j, $\Delta\overline{K}_{j,0\to T}$, against the standard deviation of industry j utilization rate, $\sigma(u_j)$ (Panel A) and against the standard deviation of average firm-level capital growth, $\sigma(\Delta\overline{K}_{j,t\to t+1})$ (Panel B). Solid line indicates best linear fit. Annual data from 1972 to 2015.

available utilization data and which feature a positive growth over the 1972-2015 sample period, consistent with a positive aggregate trend in the data and in the economic model.

We next assess a cross-sectional relationship between capital accumulation and economic uncertainty across industries. Panel A of Figure 3 shows a scatter plot of the average capital growth in industry j over the entire sample period, $\Delta\overline{K}_{j,0\to T}$, against industry j's unconditional volatility of annual capacity utilization rate, $\sigma(u_{j,t})$. In Panel B, we consider a relationship between the average capital growth and an alternative measure of industry's volatility, given by the standard deviation of the annual capital growth $\sigma(\Delta\overline{K}_{j,t\to t+1})$.

The cross-sectional evidence is consistent with our time-series aggregate-level findings. More volatile industries have higher average capital growth rates, and the relationship is statistically and economically significant. The cross-sectional correlation between $\Delta\overline{K}_{j,0\to T}$ and $\sigma(u_{j,t})$ is 0.27, with a $t-stat$ of 2.03. Likewise, the correlation between $\Delta\overline{K}_{j,0\to T}$ and $\sigma(\Delta\overline{K}_{i,t\to t+1})$ is 0.64, with a $t-stat$ of 5.11.

Micro-Level Evidence. Our benchmark analysis focuses on aggregate uncertainty and its relation to macro variables. Yet, for robustness, we show that the main facts hold at the firm-level using micro-level measures of uncertainty. Figure OA.2.5 in the Online Appendix

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shows the outcome of the following local projection:

$$y_{t+H,i} = \alpha_{i(H)} + \alpha_{t(H)} + \beta_{v(H)} v_{i,t} + \beta_{g(H)} g_{i,t} + \beta'_{control(H)} \omega_t + error,$$

where $v_{i,t}$ is a proxy for firm i's uncertainty at time t, as measured by its realized volatility of daily stock returns over the last year, $g_{i,t}$ is a proxy for firm i's first-moment shock at time t, as measured by its realized return over the last year, and additional controls ω_t include lagged investment rate, capital growth and depreciation rate. The independent variable y is either capital growth (implied from $PPENT$) or depreciation rate (implied from $PPENT$ and $CAPX$) at different horizons. Whenever significant, the impact of micro-level uncertainty on depreciation (capital growth) is negative (positive).

Alternative uncertainty measurements, controls and samples. In the first round of robustness checks we keep the benchmark measures v and g unchanged, but consider two alterations. We augment regression (4) with additional controls: the market return R_m, the nominal risk free rate r_f, and inflation rate π. Similarly, we recompute the impulse responses by appending these three controls to the vectors Y_t and ω_t. The results are shown in Panel A of the Robustness Tables (Tables 3 and 4) and Figures (Fig. OA.1.1 and Fig. OA.1.2). All panels henceforth refer to these tables and figures. For all predictive horizons, the slope coefficients β_v and associated t-statistics are almost identical in magnitude to the benchmark results. In particular, uncertainty predicts negatively (positively) depreciation (capital) growth rate, beyond the financial predictors, and the impulse response to depreciation (capital) growth remains negative (positive).

We maintain the same controls as in the benchmark specification, but change the sample period to 1968-2018, for which the utilization data are available. Panel B shows that the slope coefficient β_v retains the same sign as in the benchmark case. For both δ and K, and for horizons $H = 2, 3$, the absolute magnitude of the coefficient, and its t-statistics are quantitatively larger.

Next, we alter the construction of v and g. In Panel C, g is TFP adjusted for utilization from Fernald (2014). In Panel D, v is constructed similarly to the benchmark case, using projection (2), but when the predictor Γ_t includes only the lagged value RV_t. In Panel E,

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Table 3: **Uncertainty and depreciation: Robustness**

Horizon H	β_v	t-stat	β_g	t-stat
Panel A: Regression with financial controls				
1 years	-0.25	[-1.79]	0.25	[2.03]
2 years	-0.32	[-1.99]	0.26	[2.43]
3 years	-0.35	[-2.29]	0.18	[1.78]
Panel B: Modern sample (1968-2018)				
1 years	-0.10	[-0.91]	0.41	[2.84]
2 years	-0.25	[-2.41]	0.44	[3.31]
3 years	-0.35	[-3.14]	0.31	[2.27]
Panel C: g_t is utilization-adjusted TFP				
1 years	-0.29	[-2.26]	0.09	[0.68]
2 years	-0.37	[-2.54]	0.14	[1.27]
3 years	-0.39	[-2.85]	0.13	[1.24]
Panel D: v_t is based on RV only				
1 years	-0.27	[-2.25]	0.24	[1.90]
2 years	-0.34	[-2.30]	0.28	[2.39]
3 years	-0.35	[-2.50]	0.20	[1.82]
Panel E: v_t is based on GARCH				
1 years	-0.37	[-2.38]	0.37	[2.29]
2 years	-0.45	[-2.68]	0.43	[2.76]
3 years	-0.48	[-2.66]	0.36	[2.48]
Panel F: v_t is JLN macro uncertainty				
1 years	-0.06	[-0.48]	0.39	[2.46]
2 years	-0.32	[-2.66]	0.36	[2.58]
3 years	-0.48	[-3.39]	0.19	[1.49]
Panel G: Compustat-based depreciation				
1 years	-0.26	[-1.52]	0.11	[0.85]
2 years	-0.31	[-1.67]	0.15	[0.83]
3 years	-0.25	[-1.66]	0.13	[0.64]

The table shows the results of the regression: $\frac{1}{H}\Delta\delta_{t-1\rightarrow t+H-1} = const + \beta_{v,H}v_t + \beta_{g,H}g_t + error$. δ is private nonresidential capital depreciation rate, v is macro uncertainty, measured by the ex-ante volatility of industrial production under the benchmark predictors, and g is the real consumption growth, unless noted otherwise. In Panel A, the regression includes additional controls: the market return R_m, the 3 month T-bill yield r_f, and inflation π. Panel B uses a modern sample from 1968 to 2018. In Panel C, g is TFP adjusted for utilization from Fernald (2014). In Panel D, v is constructed using only lagged value of realized variance RV as a predictor. In Panel E, v is estimated using a GARCH(12,1) model over monthly data and averaged over the year. In panel F, v corresponds to the macro uncertainty of Jurado et al. (2015). In Panel G, the depreciation rate, δ, is measured using accounting measures from Compustat from 1964 to 2018. Annual data are from 1948 to 2018, unless noted otherwise. Standard errors are robust and Newey West adjusted. All variables are standardized.

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Table 4: **Uncertainty and capital stock: Robustness**

Horizon H	β_v	t-stat	β_g	t-stat
Panel A: Regression with financial controls				
1 years	0.26	[3.00]	0.40	[4.09]
2 years	0.25	[3.00]	0.52	[4.92]
3 years	0.25	[2.72]	0.52	[4.56]
Panel B: Modern sample (1968-2018)				
1 years	0.57	[7.94]	0.54	[5.55]
2 years	0.52	[7.22]	0.65	[7.93]
3 years	0.47	[6.12]	0.65	[8.71]
Panel C: g_t is utilization-adjusted TFP				
1 years	0.12	[1.12]	0.22	[1.85]
2 years	0.12	[1.22]	0.20	[1.85]
3 years	0.12	[1.13]	0.23	[2.04]
Panel D: v_t is based on RV only				
1 years	0.18	[1.83]	0.51	[3.82]
2 years	0.17	[1.87]	0.62	[4.78]
3 years	0.17	[1.65]	0.61	[4.51]
Panel E: v_t is based on GARCH				
1 years	0.48	[4.34]	0.36	[3.11]
2 years	0.48	[4.23]	0.47	[4.53]
3 years	0.52	[4.22]	0.46	[4.84]
Panel F: v_t is JLN macro uncertainty				
1 years	0.53	[4.79]	0.66	[6.22]
2 years	0.36	[2.50]	0.70	[7.27]
3 years	0.22	[1.42]	0.66	[6.88]
Panel G: Compustat-based capital				
1 years	0.30	[1.52]	0.23	[6.22]
2 years	0.31	[1.83]	0.22	[1.27]
3 years	0.37	[2.18]	0.20	[0.99]

The table shows the results of the regression: $\frac{1}{H}\Delta K_{t-1\to t+H-1} = const + \beta_{v,H} v_t + \beta_{g,H} g_t + error$. K is the stock of private nonresidential capital, v is macro uncertainty, measured by the ex-ante volatility of industrial production under the benchmark predictors, and g is the real consumption growth, unless noted otherwise. In Panel A, the regression includes additional controls: the market return R_m, the 3 month T-bill yield r_f, and inflation π. Panel B uses a modern sample from 1968 to 2018. In Panel C, g is TFP adjusted for utilization from Fernald (2014). In Panel D, v is constructed using only lagged value of realized variance RV as a predictor. In Panel E, v is estimated using a GARCH(12,1) model over monthly data and averaged over the year. In panel F, v corresponds to the macro uncertainty of Jurado et al. (2015). In Panel G, the capital stock, K, is measured using total Property, Plant, and Equipment item from Compustat from 1964 to 2018. Annual data are from 1948 to 2018, unless noted otherwise. Standard errors are robust and Newey West adjusted. All variables are standardized.

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we estimate v using a GARCH model over monthly industrial production, and average the volatility over the year. In panel F, v is macro uncertainty of Jurado et al. (2015). Finally, Table OA.1.2 of the Appendix shows further robustness checks, such as using the policy uncertainty of Baker et al. (2016).

In all perturbations outlined above the results are materially unchanged. Specifically, for depreciation growth, the slope coefficient β_v is always negative and significant, and the impulse response is negative and significant at least 10 years after the uncertainty shock. Broadly in-line with the baseline evidence, we find that for capital growth, the slope coefficient β_v is always positive, and the impulse responses are also positive and highly persistent, although some of the results are not significant at the 5% level.

Alternative construction of impulse responses. We maintain the benchmark proxies of g and v but use the different methodology to estimate the impact of macro uncertainty shocks on depreciation and capital growth.

Let Y_t be the vector $[g_t, v_t, \Delta\delta_t, \Delta I/K_t, \Delta K_t]'$ (in that order), where v_t is macro uncertainty measured by ex-ante industrial production volatility, g_t is consumption growth, and N is the size of the vector Y. We estimate the following vector autoregressive model:

$$Y_{t+1} = T_0 + T_{N\times N} Y_t + \varepsilon_{Y,t+1}.$$

We impose a restriction that g_t and v_t are exogenous driving forces, and therefore cannot be affected by the lagged value of the other remaining variables (that is, $T(j, 3..N) = 0, \quad j \in \{1, 2\}$).[18] We then derive impulse responses from one standard deviation uncertainty shocks to growth variables using Cholesky decomposition.

Panels (a) and (c) in Figure 4 show the impulse responses for depreciation and capital growth, respectively, estimated using the full sample period. Uncertainty shocks drop (increase) the growth in depreciation (capital), and the effect persists up to ten (five) years after the shock. For depreciation growth, the magnitude of the decline one year after the uncertainty shock is almost identical to the benchmark SLP-based evidence, shown in Panel (b) of Figure 2. For capital growth, the magnitude of the increase in the future rate is almost

[18] We obtain almost identical results without imposing this restriction.

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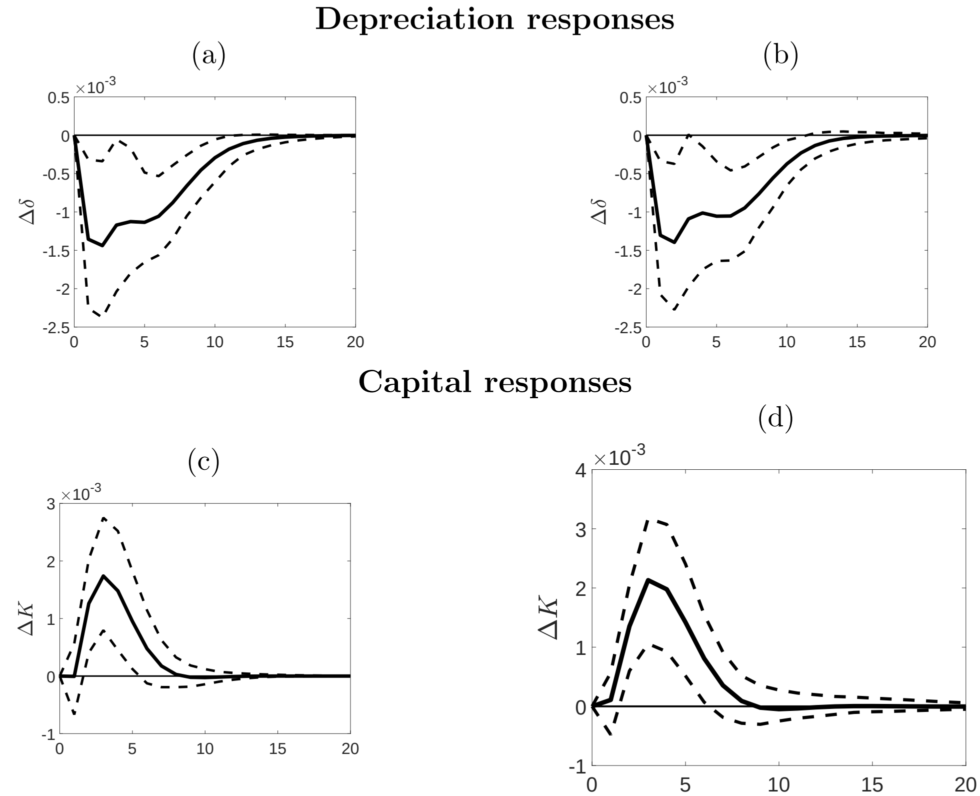
Figure 4: **Uncertainty shocks IRF: Cholesky decomposition**



The figure shows the impulse responses of depreciation growth $\Delta\delta$ (Panels (a) and (b)) and capital growth ΔK (Panels (c) and (d)) to uncertainty shocks. The impulse response functions are derived from Cholesky decomposition applied to the VAR(1) model. In Panels (a) and (c), the VAR(1) is fitted to real consumption growth, macroeconomic uncertainty, and growth rates in depreciation, investment rate, and capital, in that order. In Panels (b) and (d), the VAR(1) is augmented with the market return, 3 month T-bill yield, and inflation rate. Annual data from 1948 to 2018.

five times as large as in the benchmark evidence, shown in Panel (c) of Figure 2.[19]

In Panels (b) and (d) of Fig. 4, we augment the vector Y with the market return R_m, the 3 month T-bill yield r_f, and inflation π (in that order). The findings are qualitatively and quantitatively similar to those reported in panels (a) and (c).

The robustness checks support our evidence that high uncertainty is associated with a pronounced decline in depreciation. The effect of uncertainty on capital growth is either

[19]Uncertainty is estimated to have an insignificant impact on capital in the short-run. This is still at odds with the well-established finding that uncertainty decreases investment. Indeed, without a simultaneous movement in depreciation, capital growth should be strictly negative.

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positive or zero, but does *not* appear to be negative, in spite of a decrease in investment. In the next section, we show that our findings are challenging to reconcile within existing macroeconomic models, and develop and estimate a framework to explain the evidence.

2 Model

We construct a general-equilibrium model which can quantitatively account for our novel empirical findings, along with standard macroeconomic and asset-pricing moments. The economy is comprised of a representative household that owns a representative firm. The household has recursive preferences over future consumption. Firm uses capital and labor to produce aggregate output, and faces permanent productivity shocks whose conditional volatility is time-varying. In addition to investment and labor choices, the firm makes decisions about the utilization of the existing capital. Utilization persistently correlates with future capital depreciation, which is a key novel channel in our model.

2.1 Firm

Output. The representative firm produces its output, Y_t, using a constant return to scale Cobb-Douglas production function, over capital, K_t, and a flow of labor, L_t:

$$Y_t = A_t^{1-\alpha}(u_t K_t)^\alpha L_t^{1-\alpha}, \tag{6}$$

where α is the capital share of output, and A_t is the firm's productivity level. u_t governs the intensity with which the firm utilizes its installed capital, K_t.[20]

Capital accumulation. The representative firm owns its capital stock, K_t, which evolves according to the following law of motion:

$$K_{t+1} = (1-\delta_t)K_t + \phi\left(\frac{I_t}{K_t}\right)K_t. \tag{7}$$

[20]The fact that utilization scales capital is in line with the FRB's measurement of capacity, which primarily reflects changes in capital rather than labor (see Morin and Stevens (2005)). While utilization in Equation (6) is explicitly related to capital, the equilibrium choice of labor will implicitly depend on utilization as it affects the marginal productivity of labor (see equation (19)).

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I_t represents investment, δ_t is a time-varying and endogenous depreciation rate, and $\phi(\cdot)$ is a positive, concave function capturing adjustment costs, specified as in Jermann (1998):

$$\phi\left(\frac{I_t}{K_t}\right) = \alpha_1 + \frac{\alpha_2}{1-\frac{1}{\xi}}\left(\frac{I_t}{K_t}\right)^{1-\frac{1}{\xi}}. \tag{8}$$

The parameter ξ captures the elasticity of the investment rate. The limiting case $\xi \to \infty$ ($\xi \to 0$) represent frictionless (infinitely costly) adjustment. The parameters α_1 and α_2 are set such that there are no adjustment costs in the deterministic steady state.[21]

Capital utilization. The control variable $u_t > 0$ denotes the capacity utilization rate of the firm. This variable governs the intensity with which the firm utilizes its assets in place. We assume that increasing utilization causes existing equipment to erode faster, and therefore, a positive change in utilization is akin to a positive depreciation shock. This standard ingredient is common in extant modeling approaches (see, e.g., Jaimovich and Rebelo (2009), Basu and Bundick (2017) Garlappi and Song (2017), among others).

The current depreciation shock is given by:

$$\varepsilon_\delta(u_t) = \sigma_u\left[\frac{u_t^{1+\zeta}-1}{1+\zeta}\right]. \tag{9}$$

The parameter ζ controls the elasticity of current depreciation innovation to utilization, and determines how costly it for a firm to alter its utilization rate.[22] All else equal, larger values of ζ imply that increasing the capacity utilization rate is more costly, and ensures that firms choose a finite level of utilization. Without loss of generality, we normalize the steady-state level of utilization in the model to 1, using the scaling parameter σ_u, suggesting that the steady state value of $\varepsilon_\delta(u_t)$ is zero. When $\zeta \to \infty$, utilization is fixed at its steady-state.

Depreciation dynamics. A key ingredient of our model is the dynamics of the depreciation rate:

$$\delta_t = (1-\rho_\delta)\delta_0 + \rho_\delta\delta_{t-1} + \varepsilon_\delta(u_t). \tag{10}$$

[21]Specifically, $\alpha_1 = (\mu - 1 + \delta)^{\frac{1}{\xi}}$ and $\alpha_2 = \frac{1}{\xi-1}(1-\delta-\mu)$, where μ is the constant drift of productivity defined in Section 2.3.

[22]Notably, in Basu and Bundick (2017), the equivalent specification of Equation (9) is quadratic in the utilization rate. In untabulated results, we replace Equation (9) with the following specification: $\varepsilon_\delta(u_t) = \delta_1(u_t-1) + \frac{\delta_2}{2}(u_t-1)^2$. The results of the model are almost identical to the benchmark specification, given our estimated value of ζ.

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The parameter δ_0 is the steady-state level of the depreciation rate. The parameter $\rho_\delta \in [0,1)$ captures additional persistence in the depreciation dynamics beyond that of the endogenous utilization rate, determined by the term $\varepsilon_\delta(u_t)$.

Separating the persistence of utilization and depreciation rates is a novel element in our model, which distinguishes it from other Neo-classical and New-Keynesian models. This additional flexibility goes beyond improving the quantitative fit of the model: it plays a key role in qualitatively accounting for the impact of uncertainty on capital dynamics.

A positive ρ_δ parameter is also crucial to disentangle the persistence of the depreciation rate from that of the utilization rate. Indeed, we show in Section 2.6 that if $\rho_\delta = 0$, then the autocorrelations of utilization and depreciation are nearly identical, which contradicts the empirical evidence. Moreover, in Section 5.2 we empirically test this specification, and discuss its potential microfoundations.

Firm problem. The dividend of the firm at time t is given by:

$$D_t = Y_t - I_t - W_t L_t, \tag{11}$$

where W_t is the equilibrium wage rate. At each date t, the manager of the representative firm chooses how much to invest I_t and hire L_t, and capacity utilization u_t in order to maximize firm value given the current stock of capital K_t, the state of depreciation δ_{t-1}, wage W_t, and the stochastic discount factor of the household $M_{t,t+1}$. We can write the firm's maximization program recursively as follows:

$$V(K_t, \delta_{t-1}, A_t, \sigma_{a,t}) = \max_{L_t, I_t, u_t, K_{t+1}} \quad D_t + \mathbb{E}_t \left[M_{t,t+1} V(K_{t+1}, \delta_t, A_{t+1}, \sigma_{a,t+1}) \right] \tag{12}$$

$$\text{s.t.} \qquad (7),\ (10),\ (6),\ (11).$$

The realized unlevered return of the firm at time t is given by:

$$R_{d,t}^{\text{UNLEV}} = \frac{V_t}{V_{t-1} - D_{t-1}}.$$

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2.2 Household

The preferences of the representative household over the future consumption stream are characterized by the recursive utility of Epstein and Zin (1991):

$$U_t = \left[(1-\beta) C_t^{1-\frac{1}{\psi}} + \beta \mathbb{E}_t \left[U_{t+1}^{1-\gamma} \right]^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right]^{\frac{1}{1-\frac{1}{\psi}}}, \tag{13}$$

where γ denotes the household's coefficient of relative risk aversion, and ψ denotes its intertemporal elasticity of substitution (IES). When $\psi = \frac{1}{\gamma}$ equation (13) collapses to CRRA preferences. We assume that $\psi > \frac{1}{\gamma}$ so that the household exhibits a preference for early resolution of uncertainty, while for $\psi < \frac{1}{\gamma}$ it has a preference for late uncertainty resolution.

The household is endowed with one unit of labor. The household maximizes its utility by supplying labor and participating in financial markets. The household can hold a fraction Θ_t of the firm, which pays a dividend D_t as in equation (11). Consequently, the budget constraint of the household is given by:

$$C_t + \Theta_{t+1} V_t = W_t L_t + \Theta_t (V_t + D_t), \tag{14}$$

where L_t is the hours worked, and V_t is the stock price of the representative firm, defined in equation (12). Since the household does not derive disutility form labor, it supplies labor inelastically, and $L_t = 1$ in equilibrium.[23] The first order condition of the household's

[23] We abstract from flexible labor supply because the survey of capacity utilization conducted by the Fed relates for the most part to installed capital usage. In untabulated results (available upon request) we modify household's preferences to:

$$U_t = \left[(1-\beta) \left(C_t^{\eta} (1-L_t)^{1-\eta} \right)^{1-\frac{1}{\psi}} + \beta \mathbb{E}_t \left[U_{t+1}^{1-\gamma} \right]^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right]^{\frac{1}{1-\frac{1}{\psi}}},$$

where the η parameter is chosen such that the steady state level of labor is 20%. With flexible labor but fixed utilization, the model yields the same counterfactuals outlined later in Section 3.1. In particular, higher uncertainty leads to a precautionary labor supply, resulting in higher output following an uncertainty shock, counterfactually. Nonetheless, when we introduce flexible utilization and persistent depreciation dynamics, on top of a flexible labor supply, the macro dynamics are qualitatively identical to those described in Section 3.2. These dynamics align with the data.

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maximization program imply that the stochastic discount factor (SDF) is given by:

$$M_{t+1} = \beta \left(\frac{C_{t+1}}{C_t} \right)^{1-\frac{1}{\psi}} \left(\frac{U_{t+1}}{\mathbb{E}_t \left[U_{t+1}^{1-\gamma} \right]^{\frac{1}{1-\gamma}}} \right)^{\frac{1}{\psi}-\gamma}, \tag{15}$$

and the Euler condition for pricing any return R_j satisfies:

$$1 = \mathbb{E}_t \left[M_{t,t+1} R_{j,t+1} \right] \tag{16}$$

2.3 Productivity

Let A_t be the level of (aggregate) productivity, and $\Delta a_{t+1} = \log\left(\frac{A_{t+1}}{A_t}\right)$. We assume that log-productivity growth, Δa, follows and AR(1) process with time-varying conditional volatility governed by a process $\sigma_{a,t}$ as follows:

$$\Delta a_{t+1} = (1-\rho_a)\mu + \rho_a \Delta a_t + e^{\sigma_{a,t}} \sigma_a \varepsilon_{a,t+1}, \tag{17}$$

$$\sigma_{a,t+1} = \rho_\sigma \sigma_{a,t} + \sigma_w \varepsilon_{w,t+1}, \tag{18}$$

where $0 < \rho_a$, $\rho_\sigma < 1$, and where the productivity and volatility shocks $\varepsilon_{a,t+1}$ and $\varepsilon_{w,t+1}$ are i.i.d. standard normal, uncorrelated with each other. μ is the drift of productivity. Notably, volatility does not impact the drift, so we do not hardwire the first-order effects of volatility on the driving process. The log-volatility process σ_a is exponentiated in Equation (17) to ensure that conditional volatility is strictly positive, similarly to Equation (3) in the empirical implementation.[24] Without loss of generality, the unconditional mean of $\sigma_{a,t}$ is 0, so that the stead-state volatility of productivity growth is σ_a.

2.4 Equilibrium

An equilibrium consists of wage W_t, pricing kernel $M_{t,t+1}$, firm valuation V_t, and allocations for investment, capital, labor, utilization, depreciation, consumption, and equity hold-

[24]This log-volatility specification is shared with other general-equilibrium setups such as Croce (2014) and Basu and Bundick (2017). Importantly, there are no convergence issues that arise due to the exponentiation of the uncertainty process (as discussed in Schorfheide, Song, and Yaron (2018)), given that our setup assumes a production economy, where C_t in endogenously determined via consumption smoothing. In untabulated results, we change equation (17) such that the shock becomes $\sqrt{\tilde{\sigma}^2_{a,t}}\varepsilon_{a,t+1}$, while ensuring that the unconditional volatility $\sqrt{\tilde{\sigma}^2_{a,ss}}$ is identical to σ_a. This has a negligible impact on the quantitative model results.

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ing $\{I_t, K_{t+1}, L_t, u_t, \delta_t, C_t, \Theta_t\}_{t=0}^{\infty}$ such that: (i) Given W_t and $M_{t,t+1}$, capital, utilization, and labor allocations maximize program (12), (ii) Given W_t and V_t, consumption, labor and firm holding fraction maximize (13) subject to (14), (iii) good-market clears: $C_t + I_t = Y_t, \quad \forall t$, labor market clears: $L_t = 1, \quad \forall t$, and financial market clears: $\Theta_t = 1, \quad \forall t$.

2.5 Optimality conditions

Labor choice is static and satisfies the standard first-order condition:

$$(1-\alpha)\frac{Y_t}{L_t} = W_t. \tag{19}$$

The investment choice, I_t, is determined using the Euler equation:

$$1 = \mathbb{E}_t\Big[M_{t,t+1}R^I_{t+1}\Big], \tag{20}$$

where R^I_{t+1} denotes the returns to investment given by:

$$R^I_{t+1} = \frac{MPK_{t+1} - \frac{I_{t+1}}{K_{t+1}} + q_{t+1}\Big(1 - \delta_{t+1} + \phi(\frac{I_{t+1}}{K_{t+1}})\Big)}{q_t}., \tag{21}$$

$MPK_{t+1} = \alpha Y_{t+1}/K_{t+1}$ is the marginal product of capital at time $t+1$, and Tobin's marginal q is:

$$q_t = \phi'\left(\frac{I_t}{K_t}\right)^{-1}. \tag{22}$$

Since q_t measures the present value of an extra unit of installed capital, equation (20) shows the trade-off between the marginal cost and discounted marginal benefit of buying capital. Note that MPK_{t+1} depends positively on u_{t+1}.

Equilibrium utilization u_t is determined by the following optimality condition:

$$\frac{MPU_t}{\varepsilon'_\delta(u_t)} = q_t K_t + \mathbb{E}_t\left[M_{t,t+1}\rho_\delta \frac{MPU_{t+1}}{\varepsilon'_\delta(u_{t+1})}\right], \tag{23}$$

where MPU_t is the marginal product of utilization given by $\alpha Y_t/u_t$. Iterating forward on the right hand side of Equation (23), one obtains:

$$\frac{MPU_t}{\varepsilon'_\delta(u_t)} = \mathbb{E}_t\left[\sum_{s=0}^{\infty}\rho_\delta^s M_{t,t+s}q_{t+s}K_{t+s}\right]. \tag{24}$$

When depreciation shocks are not persistent ($\rho_\delta = 0$), the utilization choice is static:

$$MPU_t = q_t K_t \varepsilon'_\delta(u_t). \tag{25}$$

The benefit of raising utilization is its marginal contribution to output, specified on the left

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hand side of the equation. The cost of raising utilization on the right-hand side is that it causes capital to depreciate faster, which creates a cost *per dollar* of capital at a rate of ε'_δ.

When $\rho_\delta > 0$, the utilization choice is dynamic, because increased utilization raises not only the current depreciation δ_t, but also its future values $\{\delta_s\}_{s>t}$. In this case, optimal utilization can be derived from Equation (24), by plugging the expressions for output, the market clearing condition $L_t = 1$, and $\varepsilon_\delta(u_t)$:

$$u_t = \left\{ u_0 A_t^{1-\alpha} K_t^{\alpha} \mathbb{E}\left[\sum_{s=0}^{\infty} \rho_\delta^s M_{t,t+s} q_{t+s} K_{t+s} \right]^{-1} \right\}^{\frac{1}{\zeta+1-\alpha}}, \tag{26}$$

where $u_0 = \alpha\sigma_u^{-1}$. Note that when discount rates fall, the net present value of future capital increases, which creates a larger cost for utilization. The utilization choice is directly affected by the precautionary saving motive, via discount rates, similar to the investment choice.

2.6 Estimation

Table 5 shows the benchmark model parameters. Following Christiano, Eichenbaum, and Evans (2005) and Basu and Bundick (2017), we classify the parameters into two sets. The first set includes a small number of parameters that are calibrated based on existing studies. Specifically, capital's share of output, governed by α, is about 33%. We adopt a standard preference parameter configuration in the production-based asset-pricing literature: γ is set to 10, and the IES ψ is set to two. These are similar to the values employed in Barro (2009), Bansal and Yaron (2004) and Croce (2014), among others.

The second set, which includes the vast majority of the model parameters, is estimated using SMM. We denote the second set by $\theta = \{\mu,\, \rho_a,\, \sigma_a,\, \rho_\sigma,\, \sigma_w,\, \xi,\, \delta_0, \rho_\delta, \zeta,\, \beta\}$. Our estimate of θ minimizes the SMM objective function:

$$\hat{\theta} = \text{argmin}_\theta \left[\Psi(\theta) - \hat{\Psi}\right]' V^{-1} \left[\Psi(\theta) - \hat{\Psi}\right],$$

where $\hat{\Psi}$ are the empirical moments used in the estimation, $\Psi(\theta)$ are their model-implied equivalents which depend on the *monthly* parameters θ, and V is a diagonal matrix with the empirical variances of each moment along its main diagonal. Given a set of parameters, the model is solved using a third-order perturbation method. We compute model-implied

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Table 5: **Model parameters**

Parameter	Value	Description
Technology.		
μ	0.0015	Productivity growth
ρ_a	0.8919	Aggregate productivity's persistence
σ_a	0.0013	Aggregate productivity shock volatility
ρ_σ	0.9950	Log volatility's persistence
σ_w	0.0902	Log Volatility shocks' volatility
Capital.		
α	**0.34**	Capital's share of output
ξ	2	Capital adjustment cost
Depreciation and Utilization.		
δ_0	0.0075	Unconditional depreciation rate
ρ_δ	0.9908	Depreciation's persistence
ζ	0.9323	Elasticity of depreciation to utilization
Preferences.		
γ	**10**	Relative risk aversion
ψ	**2**	Intertemporal elasticity of substitution
β	0.9988	Time discount factor

The table shows the model parameters under the benchmark case (monthly frequency). All non-bold parameters are estimated via SMM. Bold parameters are calibrated.

moments based on 200 simulations of short sample paths of 612 months each. Each model-implied path is time-aggregated to annual observations spanning 51 years, which matches a modern empirical sample from 1968 to 2018 for which utilization growth data are available.

Table 6 shows the moment conditions used to estimate the model. We group the moments into two categories.[25] (A) Unconditional annual moments: the mean, standard deviation, and autocorrelation of consumption growth, output growth, investment growth, depreciation rate and real risk-free rate; the standard deviation and autocorrelation of utilization rate. (B) Realized volatility moments: the standard deviation and autocorrelation of rolling window realized volatility time-series for consumption, output and investment growth rates. In all, we use 23 moment conditions to identify 10 parameters. Importantly, we refrain from identifying ζ (and other parameters) by targeting the impulse-responses of uncertainty shocks to capital or to depreciation, to ensure that any model-implied increase in the capital stock following

[25]The table shows all macro-related moments used in the estimation. See Table 7 for the risk-free rate moment.

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Table 6: **Model-implied macroeconomic moments**

	Model		Data
Panel A: Unconditional annual moments.			
Consumption growth.			
Mean (%)	1.82	[0.60, 3.69]	1.81
Std. Dev. (%)	2.16	[1.20, 4.73]	1.22
AC(1)	0.46	[0.15, 0.71]	0.47
Output growth.			
Mean (%)	1.85	[0.54, 3.81]	1.78
Std. Dev. (%)	2.43	[1.37, 5.63]	1.92
AC(1)	0.47	[0.16, 0.68]	0.25
Investment growth.			
Mean (%)	1.86	[0.35, 3.93]	1.25
Std. Dev. (%)	3.31	[1.70, 7.77]	5.83
AC(1)	0.39	[0.11, 0.63]	0.27
Depreciation rate.			
Mean (%)	8.18	[7.23, 9.51]	8.34
Std. Dev. (%)	0.32	[0.12, 0.72]	0.51
AC(1)	0.98	[0.93, 0.99]	0.96
Utilization rate.			
Std. Dev. (%)	4.74	[2.86, 8.55]	4.17
AC(1)	0.77	[0.39, 0.92]	0.62
Panel B: Realized volatility moments.			
Consumption growth.			
Std. Dev. (%)	0.19	[0.08, 0.54]	0.14
AC(1)	0.97	[0.91, 0.99]	0.97
Output growth.			
Std. Dev. (%)	0.26	[0.10, 0.78]	0.30
AC(1)	0.98	[0.94, 0.99]	0.98
Investment growth.			
Std. Dev. (%)	0.48	[0.17, 1.36]	0.63
AC(1)	0.98	[0.91, 0.99]	0.96

The table shows model-implied moments along with their empirical counterparts. Panel A shows unconditional moments for macroeconomic growth and rate variables. Panel B shows realized volatility moments computed using a 5-year rolling window standard deviation. For each moment of interest, the table shows the median value and the 5th and 95th percentiles based on 200 simulation of short sample paths 612 months each. In Panel A (B) each model-implied path is aggregated to form annual (quarterly) observations spanning 51 years (204 quarters). The empirical moments are based on a modern sample from 1968 to 2018.

higher uncertainty is not mechanically hardwired by the estimation exercise. We examine the fit of the model to the impulse response evidence in Section 3.2.2.

In our model estimation, the means of annual consumption, output, and investment growth jointly help to identify the parameter μ. We estimate μ to be about 0.15%, which implies an annual real consumption growth rate of 1.82%, consistent with its empirical

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value of 1.81%. The standard deviation (autocorrelation) of consumption growth is directly governed by σ_a (ρ_a). Under the estimated values, the model-implied volatility of consumption growth is about 2%. The lower bound of the model confidence interval is about 1.2%, which aligns with the data from 1968 onward. Moreover, consumption growth volatility is about 2% at the long-run sample from 1930 to 2018. The autocorrelation of consumption growth is 0.46 and 0.47 in the model and the data, respectively. The capital adjustment cost ξ is identified by targeting the volatility and the autocorrelation of output and investment growth rates. These empirical moments fall within the model's confidence intervals.

To identify the parameters that govern the uncertainty process, σ_w and ρ_w, we construct realized volatility time-series for consumption, output, and investment quarterly (3 month) growth rates, using a five year (20 quarters) rolling window standard deviation. We then compute the standard deviation of these realized volatilities. If the data featured constant conditional volatility, the standard deviations of the five-year rolling realized volatilities would be close to zero. By contrast, these standard deviations are statistically significant, and amount to 0.14%, 0.3%, and 0.63%, for the realized volatility of consumption, output, and investment growth, respectively. The model equivalents are 0.19%, 0.26% and 0.48%, respectively, all close to the data.

To help identify ρ_w separately from σ_w the estimation also includes the autocorrelation of these realized volatility time-series. The estimated uncertainty process is highly persistent, and implies that the autocorrelation of the five-year rolling window standard deviations are all above 0.97 in the model, similar to the data.

The parameters δ_0 and ρ_δ are identified using the mean and the autocorrelation of depreciation, respectively. δ_0 is estimated to be 0.75%, suggesting that the model-implied annualized average depreciation rate is 8.18%, closely matching the empirical rate. ρ_δ is estimated to be about 0.99 at the monthly frequency, consistent with modeling the depreciation dynamics as persistent.[26] Given this estimate, the autocorrelation of the annual depreciation

[26] In untabulated results, we repeat the estimation exercise when targeting the volatility and autocorrelation of depreciation growth, rather than depreciation rate. Our estimate for ρ_δ in this case is nearly identical, given that the annual AC(1) of $\Delta\delta$ is about 0.93.

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rate is 0.98 in the model versus 0.96 in the data. At the same time, the autocorrelation of the utilization rate is 0.77 in the model versus 0.62 in the data, with an upper bound of 0.92. Thus, both empirically and theoretically, the autocorrelation of the depreciation and the utilization rates are statistically distinct, with the former being more persistent than the latter. Importantly, if ρ_δ is set to zero, as in other existing frameworks, the model-implied autocorrelation of utilization and depreciation would be counterfactually identical.

The parameter ζ, which governs the elasticity of depreciation to utilization, is identified by targeting the unconditional volatility of utilization rate, which amounts to 4.2% in the data, jointly with the volatility of the depreciation rate, which is 0.5%. Both volatilities fall within the model's confidence interval.

Lastly, the estimate of β is 0.998, identified using the mean, standard deviation, and autocorrelation of the risk-free rate. The risk-free rate is 0.91% (1.04%) in the model (data).

3 Implications for the macroeconomy

We show that our model is able to quantitatively account for the key empirical evidence, and specifically: (a) negative association between uncertainty and depreciation, and (b) positive association between uncertainty and future capital growth, in spite of a drop in investment. We start by illustrating the failure of the model with fixed utilization to generate these findings. In particular, the fixed-utilization model implies a counterfactual increase in investment following an uncertainty shock, and fails to produce an uncertainty-driven recession. We then show in Subsection 3.2 that flexible utilization coupled with persistence in depreciation go a long way to account for these features of the data.

3.1 Case I: A model with fixed utilization

We show that a model with fixed utilization ($\zeta \to \infty$) is unable to explain the empirical evidence. Figure 5 shows model-implied cumulative impulse responses (IR) of the key macroeconomic variables to a one-standard deviation uncertainty shock. The dashed line shows the results for a model with fixed utilization.

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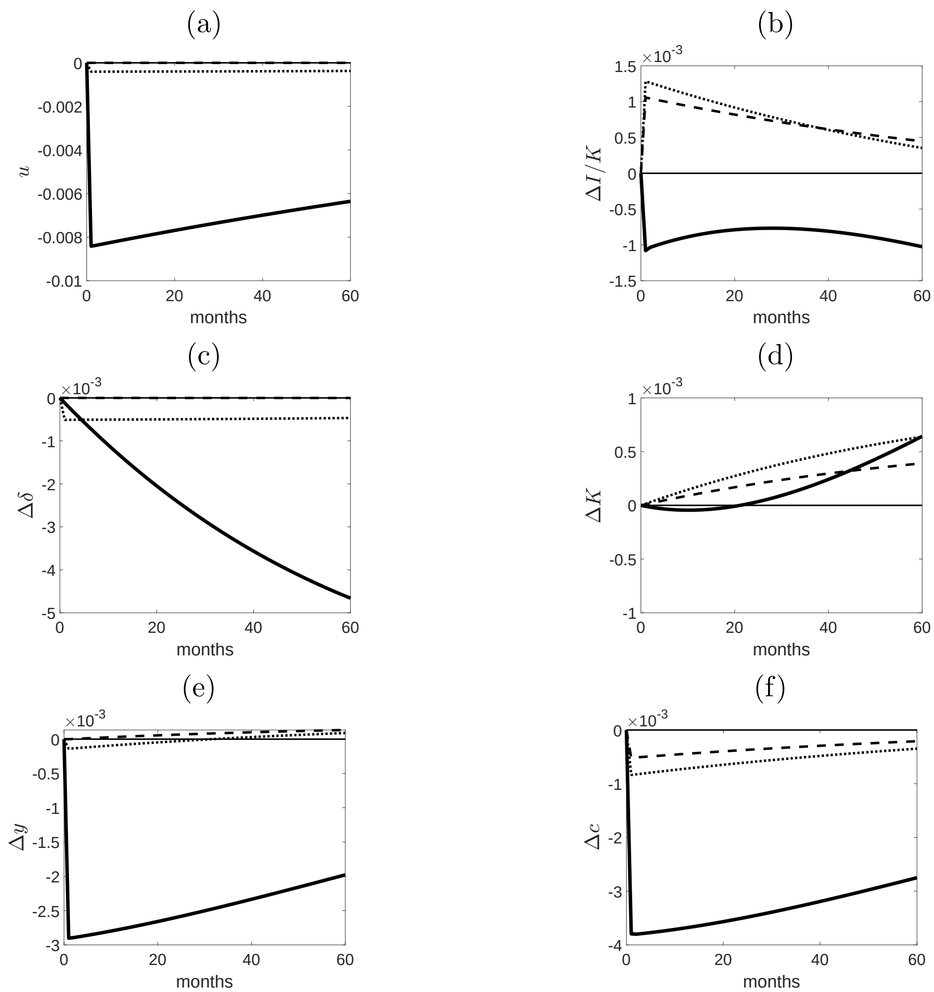
Figure 5: **Model-implied IR to uncertainty shocks: macro growth**



The figure shows the impulse responses of (a) utilization rate u, and the growth rates of (b) investment rate $\Delta I/K$, (c) depreciation rate $\Delta\delta$, (d) capital stock ΔK, (e) output y, and (f) consumption c to uncertainty shocks. The solid line shows the results using the benchmark model parameters. The dotted line shows the results when $\rho_\delta = 0$ (no extra persistence in depreciation). The dashed line shows the results when $\zeta \to \infty$ (fixed utilization). All growth impulse responses are cumulative. The horizontal axis represents months. The vertical axis represents deviations from the steady-state value.

Utilization, depreciation, and investment. A surge in uncertainty raises the volatility of future productivity, and increases the likelihood of future output declines. A risk-averse household has strong incentives to create a buffer to smooth out future consumption fluctuations. When utilization is fixed, the firms optimally implement precautionary savings by

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investing and building up a stock of capital that can be used for consumption in the future.[27]

To see this mechanism through the optimality conditions, note that an increase in the uncertainty raises the volatility of the SDF $M_{t,t+1}$, and decreases the equilibrium risk-free rates, consistent with the precautionary savings channel. This drop in the discount rate increases the present value of the expected marginal product of capital.[28] Thus, an immediate implication of the Euler equation (21) is that the firm increases its investment I_t. This is consistent with the model-implied impulse response in panel (b) of Figure 5 , but is contrary to the empirical evidence presented in Table 2, or Figure 2.

Because utilization is fixed, the depreciation rate is constant and is unaffected by uncertainty. Accordingly, panels (a) and (c) of Figure 5 show no impact of uncertainty shocks on u_t or δ_t. This is at odds with the evidence in Table 2.

Capital growth. Given that investment rises and depreciation is unaltered, capital growth must rise, as shown in panel (d) of the Figure. The increase in capital, however, occurs *because* of an increase in investment (panel b), which is contrary to the data.

Output and consumption. Because capital K_t is predetermined, labor supply is inelastic, and current productivity A_t is unaffected by uncertainty, the current output Y_t does not react on impact to the uncertainty shocks (see dashed line in panel (e) of Figure 5). Future output growth increases due to the capital build-up induced by precautionary saving. This goes against existing evidence that uncertainty is associated with a drop in future output (e.g., Ludvigson et al. (2021), among others). It is important to note that elastic labor supply would not resolve this counterfactual. With flexible labor, uncertainty would induce a precautionary labor supply, which would raise not only the future output growth but also the contemporaneous one.

[27] A necessary condition for uncertainty to induce this precautionary saving effect is Decreasing Absolute Risk Aversion (see e.g. Leland, 1968 ; Kimball and Weil, 2009), satisfied by Epstein and Zin (1989a) utility.

[28] Higher macro uncertainty also increases the quantity of risk in the economy, and as a result, raises risk premia. While this channel offsets, to some degree, the decline in the risk-free rate, the overall discount rate drops. This outcome is widespread in general-equilibrium models featuring fixed utilization (see, e.g., Croce (2014), among others). As discussed later in Section 4, when utilization is fixed, the contribution of uncertainty shocks to the equity premium is counter-factually negative, leading to a muted change in the risk premium.

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Since contemporaneous output is unaffected and investment increases due to uncertainty shocks, consumption growth must drop for the goods market to clear. Future consumption is persistently negative due to the fact that the volatility process is persistent, suggesting persistence in the precautionary saving motive (see panel (f) of the Figure). While a decrease in consumption growth is consistent with the empirical evidence (see, e.g., Bansal, Kiku, Shaliastovich, and Yaron, 2014), its negative correlation with investment is counterfactual.

Lastly, we emphasize that the failures of the fixed-utilization model outlined above only hinge on the model featuring decreasing absolute risk aversion. While the magnitude of mismatch could have changed had we re-calibrated the model with fixed utilization, the *qualitative* implications would have remain unchanged.

3.2 Case II: Flexible utilization and persistent depreciation

Next, we show that flexible utilization and persistent depreciation dynamics resolve the counterfactual implications of the restricted model, and allow us to account for the empirical evidence. The solid lines in panels (a) – (f) of Figure 5 shows model-implied cumulative impulse responses to an uncertainty shock under the benchmark model parameters.

Utilization, depreciation, and investment. Equation (26), describing the optimal choice of capacity utilization, explicitly links utilization to the depreciation rate: higher utilization erodes capital faster. When depreciation effects are persistent, utilization costs are intertemporal – and take into account not just the value of the existing capital stock, but also its expectations of future realizations. The more persistent depreciation is, the greater is the present value of the affected stock of capital, and the larger is the cost of utilization.

As explained in Subsection 3.1, a positive uncertainty shock ε_w causes the risk-free rate to persistently decline. The the net present value of future capital stocks in Equation (26) increases. Thus, based on Equation (26), the cost of utilization rises. In equivalent terms, the firm can benefit by lowering its utilization rate, which would persistently lower depreciation, and therefore increase the capital stock in future periods. The future capital stock becomes more valuable in present value due to the decline in discount rates. Because the uncertainty process is persistent, the same logic applies to future periods and suggests a drop both in the

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contemporaneous and the future utilization rate $\{u_s\}_{s\geq t}$, as seen in the solid line of panel (a) of Figure 5.

As a direct result of Equation (10), and the fact that u_t declines, the depreciation growth rate also declines following an uncertainty shock, as illustrated in panel (c) of Figure 5. This is consistent with the empirical evidence in Table 2 and Figure 2. The persistence parameter $\rho_\delta > 0$ magnifies the contemporaneous drops in utilization and depreciation, and generates long-lasting effects of uncertainty on these variables.

Under flexible utilization, the uncertainty shock ε_w renders two opposite forces on investment: (1) as in Subsection 3.1 the risk-free rate R_f falls, which increases the expected discounted value of the future MPK_{t+s}, all else equal. This is part of the precautionary saving motive, and it operates to increase I_t. (2) The future utilization rate declines, based on panel (a). A decline in u_{t+s} is isomorphic to a drop in future productivity. To see this, note that the equilibrium MPK_{t+s} can be rewritten as $SR_{t+s}K_{t+s}^{\alpha-1}$, where the Solow residual, SR_{t+s}, is $\alpha A_{t+s}^{1-\alpha}u_{t+s}^{\alpha}$. Thus, lower u_{t+s} decreases the future value of MPK_{t+s}, and this operates to decrease I_t. In our benchmark parametrization, the effect of (2) dominates.[29] Hence, investment growth persistently declines following an increase in uncertainty, as shown in panel (b) of Figure 5, consistent with the empirical evidence Table 2.

Thus, our channel, relying on flexible utilization coupled with persistent depreciation, alters the qualitative effects of uncertainty shocks, vis-a-vis the restricted model in Section 3.1. When utilization is flexible, and can be lowered at times of high uncertainty, it replaces an increase in investment for executing precautionary saving. Lowering utilization decreases capital depreciation rate, preserves capital for future periods as a buffer against bad productivity shocks, and without the need to pay an installation cost associated with purchasing new capital goods (i.e., adjustment costs). This substitution between utilization and investment for saving allows us to account for the empirical evidence, and explain the joint dynamics of output and consumption, as shown below.

Capital growth. Panel (d) of Figure 5 shows the impact of an uncertainty shock on

[29]Specifically, the utilization growth rate immediately drops by 0.8% after an uncertainty shock, whereas R_f (not shown in Figure 5) drops by 0.01%.

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cumulative capital growth in the model. Cumulative capital growth overshoots after about 20 months, whereas the initial effect of uncertainty on capital is close to zero.[30] This pattern resembles the data: the empirical analysis shows that following an uncertainty shock, capital growth either increases in *future* periods, or at a minimum, is unaffected in the immediate run. In particular, panels (c) and (d) of Figure 4 show that capital growth's impulse response is indistinguishable from zero in the first two years, but turns positive thereafter. Therefore, the model dynamics are consistent with our novel evidence that uncertainty does *not* decrease capital growth in the longer run (see further details on the model fit in Section 3.2.2).

Two channels affect the sign of capital growth in the model: First, keeping depreciation constant, the decrease in investment in response to uncertainty leads to a drop in capital growth. Second, keeping investment constant, the decrease in depreciation in response to uncertainty increases capital growth. The parameter which governs the magnitude of the impact of utilization on depreciation is σ_u (see Equations (9) and (10)). In our model, it is set to a relatively small value, to match the utilization and depreciation moments in the data (in particular, it disciplines the mean of utilization). Thus, the immediate effect of utilization on depreciation is sufficiently small so that the first channel dominates in the immediate run. However, the impact of uncertainty on utilization is much more long-lasting than on investment; see panels (a) and (d) of Figure 2. Coupled with a persistent effect of utilization on depreciation ($\rho_\delta > 0$), the cumulative effect of under-utilizing capital *intensifies* over time. In one-two years following the uncertainty shock, the effect of a decrease in depreciation dominates the decrease in investment, and boosts medium- to long- term capital growth.

We note that existing papers that produce a decline in investment following an uncertainty shock (e.g., using real options, Bloom (2009), or an increase in the risk premium, Di Tella and Hall (2021)), typically assume that the depreciation rate is constant, and consequently, are unable to reconcile the divergence between investment and capital growth following uncertainty shocks.[31]

[30]The non-cumulative impulse response to capital growth turns positive already after 10 months.

[31]Even if depreciation is time-varying, existing channels for uncertainty-induced recessions can fail to deliver this finding. For example, Basu and Bundick (2017) use countercyclical markups to make investment drop in response to uncertainty. Their model features flexible utilization which induces time-varying de-

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We highlight that the model-implied divergence between capital growth and investment occurs only with respect to second-moment productivity shocks. While such divergence can potentially arise from first-moment shocks, the quantitative impact of these shocks on investment is larger than their impact on depreciation, yielding comovement between investment and capital growth in this case (hence, capital growth is procyclical, as in the data).

Output and consumption. In contrast to a model with fixed utilization, contemporaneous output can decrease with uncertainty, because of the immediate drop in the utilization rate. The future growth in output depends on the balance between the decrease in future utilization and investment rates, and the increase in future capital due to a fall in the depreciation rate. The impulse responses show that a drop in utilization (panel a) dominates an increase in capital (panel b), which leads to a decline in output in the future (panel e)).

Lastly, via market clearing, consumption is the difference between output and investment. Following an uncertainty shock, output growth falls more strongly than investment growth, causing consumption to decrease contemporaneously and in the future. Intuitively, investment is driven by two countervailing forces – a precautionary saving motive versus a drop in the future effective productivity caused by lower utilization. This weakens the response of investment to uncertainty shocks, compared to the response of output to these shocks. While consumption growth also decreases in the model with fixed utilization (see Subsection 3.1), the consumption drop is smaller in that case compared to the flexible utilization model.

3.2.1 The role of persistence in depreciation

We show that persistent depreciation ($\rho_\delta > 0$), in excess of the endogenous persistence in utilization, is a key ingredient for our results. Flexible utilization alone is not sufficient for the model to fully explain the novel features of the data. The dotted line in panels (a) – (f) of Figure 5 shows model-implied cumulative impulse responses to an uncertainty shock ε_w with flexible utilization but no additional persistence in depreciation ($\rho_\delta = 0$).

preciation. Utilization in their model has only a quantitative, but not a qualitative impact on the results. In particular, because the authors do not assume that depreciation dynamics are persistent, we confirm in Online Appendix Figure OA.1.4 that an uncertainty shock leads to a drop in both investment and future capital growth in their model, in contrast to our evidence.

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There are two major differences in uncertainty's impulse responses under this case compared to the case of extra persistence in depreciation. First, while some of the qualitative responses are similar to the case of $\rho_\delta > 0$, the quantitative magnitudes are minuscule compared to the case of $\rho_\delta > 0$. For example, utilization growth immediately declines by 0.02% versus 0.6%, when $\rho_\delta = 0$ and $\rho_\delta = 0.99$, respectively. Similarly, consumption growth falls by 0.05% (0.25%) without (with) additional persistence in depreciation dynamics.

As shown in Section 2.5, when $\rho_\delta = 0$ the utilization's choice is static. The benefit of reducing utilization is that it slows down the depreciation rate when a capital build up is beneficial for the agent. With $\rho_\delta = 0$, this benefit only pertains to the contemporaneous stock. The precautionary effect which creates a dynamic link between utilization, discount rates, and the capital stock in future periods disappears. Thus, the decline in utilization following an uncertainty shock is much smaller, and this affects other variables of interest.

The drop in the magnitude of utilization's response qualitatively affects the investment dynamics. Panel (b) shows that if $\rho_\delta = 0$, the investment rate growth increases, despite the decrease in utilization. Recall that investment is determined by the trade-off between a drop in discount rates and a drop in Solow residual which positively depends on utilization. If the change in utilization growth is minor, the discount rate effect dominates, leading to precautionary saving primarily through higher investment, contrary to the data.

3.2.2 Quantitative comparison

The impulse responses in the model depicted in Figure 5 are monthly and cumulative, and consequently, cannot be directly compared to the empirical responses in Figure 2, which are annual and non-cumulative. To help assess the quantitative fit of the model to the data, we construct an empirically-equivalent response to uncertainty shock within the model. Specifically, we scale the model-implied uncertainty shock such that it raises the one-year ahead uncertainty in the model with an identical magnitude to the one-year ahead impulse response in the data. In addition to the point estimate, we use the 95% empirical confidence interval to one-year ahead uncertainty to construct the bounds for the uncertainty shock within the model. Lastly, we sample the model-implied responses every four quarters such

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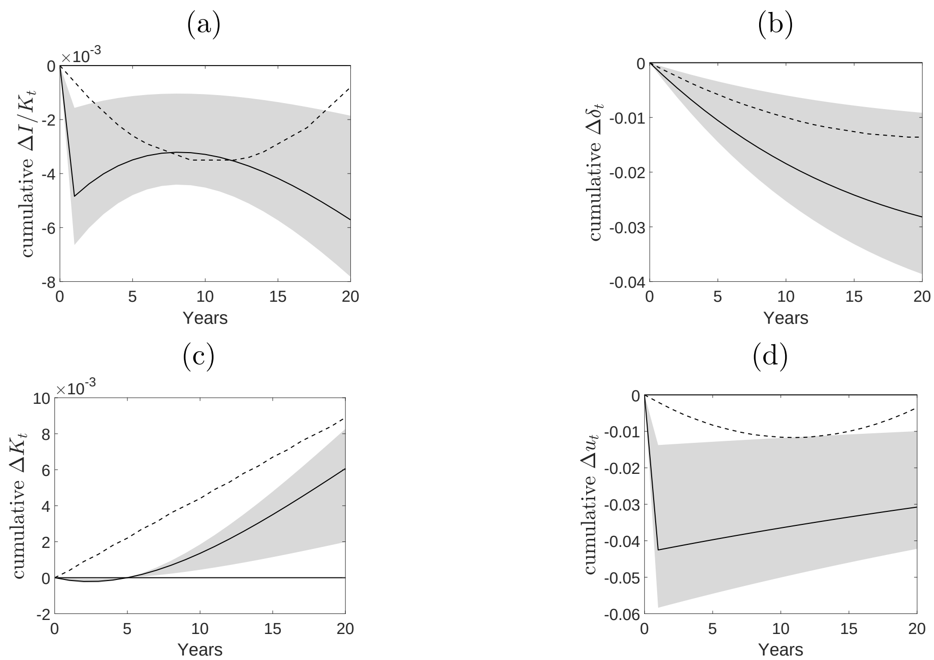
Figure 6: **Uncertainty shocks cumulative IR: model vs data**



The figure shows model-implied empirically-equivalent impulse responses (black) and empirical impulse responses (dashed) of the growth rate of (a) investment rate $\Delta I/K$, (b) depreciation rate $\Delta\delta$, (c) capital stock ΔK, and (d) utilization rate Δu, to uncertainty shocks

that the frequency of the observations is annual.

Figure 6 shows model-implied cumulative impulse responses of the log-growth rates in investment, depreciation, capital, and utilization to the empirically-equivalent uncertainty shock. Confidence intervals are shown in shaded regions. The data are shown in dashed lines, obtained by accumulating the impulse responses from 0 up to horizon h in Figure 2.

Importantly, the structural estimation of the model only depends on unconditional moments, and does not target these impulse responses. Nonetheless, the model provides a reasonable fit to the data. For most horizons, the empirical cumulative impulse responses to depreciation and investment growth fall within the model bounds. The model-implied impulse response to capital (utilization) growth somewhat understates (overstates) the empirical equivalent, albeit the upper (lower) bound is close to the data at longer horizons.

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3.2.3 Comparison to the New-Keynesian approach

Basu and Bundick (2017) and Fernández-Villaverde et al. (2015) show that a new-Keynesian model featuring time-varying markups can induce a comovement between consumption and investment in response to uncertainty shocks. In Appendix OA.3 we extend our baseline model to accommodate our economic channel which relies on flexible utilization and persistent depreciation as well as the economic channel of countercyclical markups.

We show that under our baseline parameter values and permanent productivity shocks, time-varying markups alone do not cause investment to decline following an uncertainty shock. However, when we incorporate extra persistence to depreciation, the impulse responses to consumption, investment and output are all negative. We also show that under transitory productivity shocks, time-varying markups can make investment drop in response to uncertainty. When persistent depreciation is added in this case, the impulse responses to consumption and output are significantly amplified in absolute terms.

4 Implications for asset prices

We show that our model is capable of producing a sizable equity premium, and that a considerable component of the equity premium is due to the uncertainty shocks.

Unconditional moments. As is, our benchmark specification for the firm valuation cannot be directly compared to the data. In the model, firms are all-equity financed, and there is no operating leverage incurred by fixed costs. In reality, firms take a substantial amount of financial and operating leverage. Further, dividend cash flow in the model is the residual output net of investment and wages; in the data, distributions to the shareholders can be subject to firms-specific payout shocks. To bring the model closer to the data, we follow Croce (2014) and consider the following levered return as a proxy for the market excess return:

$$R^e_{m,t} = \phi_{lev}(R^{\text{UNLEV}}_{d,t} - R_{f,t-1}) + \sigma_d \varepsilon_{d,t},$$

where $\varepsilon_{d,t} \sim N(0,1)$ captures the effect of idiosyncratic dividend shocks. García-Feijóo and

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Table 7: **Model-implied asset prices**

Panel A: Asset pricing moments

	Model		Data
Market Excess Return.			
Mean (%)	7.29	[2.43, 12.97]	4.58
Std. Dev. (%)	17.78	[13.94, 22.47]	17.09
AC(1)	-0.01	[-0.23, 0.26]	-0.05
Risk-free rate.			
Mean (%)	0.91	[0.33, 1.79]	1.04
Std. Dev. (%)	1.20	[0.69, 2.20]	1.71
AC(1)	0.58	[0.29, 0.77]	0.79

Panel B: Equity premium decomposition

	$E[R_m^e]$ (%)	Contribution First-Moment	Contribution Second-Moment	$\sigma(\Delta c)$ (%)
(1) Data	4.58	-	-	1.22
(2) Benchmark	7.29	73.24%	26.75%	2.16
(3) Fixed Utilization	2.21	196.82%	-96.82%	1.90
(4) No extra persistence in depreciation	2.20	207.07%	-107.07%	1.90

Panel A of the table shows model-implied asset-pricing moments along with their empirical counterparts. Panel B of the table shows the empirical and model-implied moments for the equity premium $E[R_m^e]$, and the decomposition of the equity premium to first- and second- moments of productivity shocks. The risk-premium contribution of each shock is computed as the multiplication of the unconditional market exposure to the shock multiplied by the average market risk-price of the shock. Market exposures (risk-prices) are obtained using model-implied impulse-responses from the shock of interest to the market excess return (negative of the SDF). To compute the share of each shock, we divide the shock's risk premium by the total market risk premium. For ease of comparison across calibrations, we also report consumption growth's volatility $\sigma(\Delta c)$. The results are shown for a calibration under the benchmark parameter values; and restricted calibrations with feature fixed utilization ($\zeta \to \infty$), or flexible utilization but no extra persistence in depreciation dynamics ($\rho_\delta = 0$). For each moment of interest, the table shows the median value and the 5th and 95th percentiles based on 200 simulation of short sample paths 612 months each. Each model-implied path is aggregated to an annual horizon. The empirical moments are based on a modern sample (1968-2018) of annual observations.

Jorgensen (2010) estimate that the total degree of leverage (joint operating and financial leverage) implies $\phi_{lev} = 3.5$. This estimate is consistent with the leverage parameter in Abel (1990), and Bansal and Yaron (2004). The shocks $\varepsilon_{d,t}$ do not covary with the marginal utility, and do not affect the equity premium. These shocks only impact excess returns' volatility.

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We set σ_d to target the volatility of excess returns in the data.

Unconditional pricing moments. Panel (a) of Table 7 shows the model-implied moments of the excess equity returns and the risk free rate. Accounting for financial leverage and idiosyncratic dividend shocks, the model can match the key features of the equity return in the data. In the data, the mean of the excess returns is 4.58% (with a 95%-CI of [0.18%, 9.47%]). The model-implied average excess return is 7.29%, close to the data and well inside the empirical CI. In the data, the volatility of the market excess returns is 17.09% per annum, which is nearly identical to the volatility of excess returns in the model. The autocorrelation of the returns in both the model and the data is close to zero. The risk free rate is about 1% in both the model and the data. The risk free rate in the model is sufficiently smooth, and features similar persistence as in the data.

First-moment shocks contribution. Panel (B) in Table 7 shows that about 73% of the equity premium contribution originates from first-moment productivity shocks. As demonstrated in Croce (2014), attaining a sizable equity premium in general-equilibrium is a considerable challenge, in the absence of a slow-moving productivity process.

However, our model can endogenously generate sizable variation in long-run consumption risk through two channels: (a) as shown by Kaltenbrunner and Lochstoer (2010), investment can create long run risk. That is, consumption smoothing via investment implies that consumption growth features an expected component; and (b) uniquely to our setup, *flexible utilization* also creates sizable long run risk, because of the persistent depreciation dynamics. Put differently, any change in utilization creates a small but persistent depreciation shock via Equation (10), yielding a slowly decaying fluctuation in the future capital stock, which is translated into a small predictable component in consumption growth.

Uncertainty shocks contribution. Panel (a) of Figure 7 shows that in our benchmark model, uncertainty shocks increase the marginal utility. Notably, the quantitative impact of uncertainty shocks on the stochastic discount factor – i.e., the market price of uncertainty risks – remains quite similar in model specifications with fixed utilization ($\zeta \to \infty$) or with no extra persistence in depreciation $\rho_\delta = 0$.

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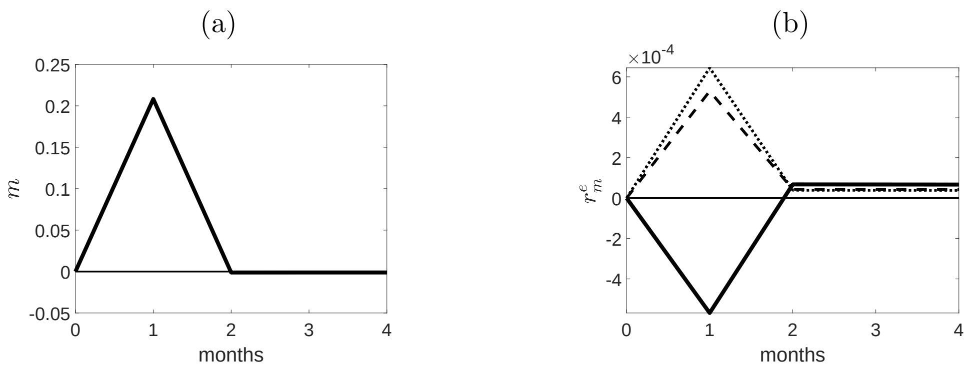
Figure 7: **Model-implied IR to uncertainty shocks: prices**



The figure shows impulse responses of (a) the marginal utility m, (b) excess returns, r^e_d to uncertainty shocks. The solid line shows the results using the benchmark model parameters. The dotted line shows the results when $\rho_\delta = 0$ (no extra persistence in depreciation). The dashed line shows the results when $\zeta \to \infty$ (fixed utilization). All growth impulse responses are cumulative. The horizontal axis represents months. The vertical axis represents deviations from the steady-state value.

Intuitively, with Epstein and Zin (1991) utility and preference for early resolution of uncertainty, the continuation utility decreases with a more volatile consumption profile, which increases $M_{t-t,t}$. In our model, the firm's production function features constant returns to scale, and consequently, valuation and investment comove. Simply put, Tobin's q is a sufficient statistic for the (ex-dividend) firm value, and Equation (22) suggests that q depends positively on I_t/K_t. Consider case I from section 3.1, in which utilization is fixed. The section shows that uncertainty shocks increase investment due to a precautionary saving motive. This implies that the firm valuation increases with uncertainty; indeed, the dashed line in panel (b) in Figure 7 shows that the firm realized excess return increases after an uncertainty shock, yielding a positive risk exposure.[32] Since the firm value is a hedge against uncertainty shocks, the uncertainty shocks contribute negatively to the risk premium. The quantitative contribution of uncertainty shocks to the equity premium in the steady-state can be approximated by the negative of the product of the impulse response of the marginal utility and the impulse response of the excess return at time $t = 1$ (i.e., contemporaneously with the uncertainty shock). As shown in row (3) of Panel (B) in Table 7, with fixed utilization

[32]The impulse responses in Figure 7 are to the unlevered equity return, $R^{\text{UNLEV}}_{d,t}$. The impulse responses to the levered return R_m are identical up to the scale factor ϕ_{lev}.

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the contribution of uncertainty shock to the equity premium is -96.8%. The equity premium under fixed utilization is considerably lower than the benchmark equity premium, despite the fact that the two specifications feature nearly identical consumption volatility; see Table 7.

Panel B of Figure 7 further shows that in the case of no extra persistence in depreciation, the firm beta to uncertainty risks is positive and even larger than with fixed utilization. Hence, the risk premium for uncertainty shocks remains negative, and the overall equity premium is well below the benchmark specification.

In contrast, when utilization turns flexible and has a persistent effect on depreciation, precautionary saving is no longer accomplished by investment, but rather by decreasing utilization. Since investment drops, the firm risk exposure to uncertainty shocks is now negative, as shown by the drop in realized return in panel (b) of Figure 7. As shown in row (2) of Panel (B) in Table 7, in the benchmark model specification uncertainty shocks contribute sizably to the total equity premium, at just over 26%. In all, our novel mechanism overturns the counterfactual pricing implications of uncertainty under a fixed-utilization model and provides a parsimonious way to qualitatively explain the empirical connection between uncertainty and stock prices in a general-equilibrium setup.

5 Assessing the mechanism

5.1 Utilization and volatility risk

Our mechanism provides testable predictions for the connection between utilization, uncertainty, and asset prices which we can assess in the cross-section of returns. First, the model predicts that the uncertainty exposures of firm return and its utilization rate are related: the more sensitive the utilization is with respect to aggregate uncertainty, the larger, in absolute value, is the firm's uncertainty beta. Similarly, the model predicts a negative relationship between the volatility of utilization and asset return uncertainty risk exposure.

The intuition is as follows. Cutting utilization in response to an uncertainty shock benefits the firm by conserving more capital against future bad shocks. When utilization is

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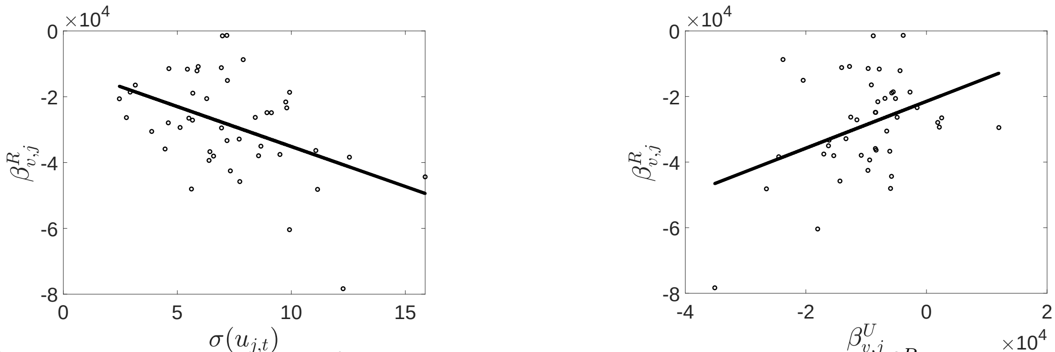
Figure 8: **Uncertainty risk exposures against utilization-elasticities**

(a) (b)



The figure shows a scatter plot of industry j return beta to uncertainty risks, $\beta^R_{v,j}$, against industry j's standard deviation of utilization rate, $\sigma(u_j)$ (panel a) or industry j utilization beta to uncertainty risks, $\beta^U_{v,j}$. Solid line indicates best linear fit. Annual data from 1975 to 2015.

more flexible (i.e., $\uparrow \sigma(u)$, more volatile utilization governed by lower ζ), the firm can drop its utilization rate more aggressively, which implies higher sensitivity of utilization to uncertainty. A sharper persistent drop in utilization lowers the expected MPK more strongly. This yields a larger decrease in investment and in Tobin's q (valuation), leading to a more negative exposure to uncertainty shocks.

We verify these predictions using annual industry-level utilization rates from the FRB's report on Industrial Production and Capacity Utilization (report G.17). The cross-section encompasses durable producers (18 industries), nondurable producers (17 industries), and mining and utilities (10 industries). The time period of the cross-sectional data ranges from 1972 to 2015. We estimate for each industry j its macro uncertainty exposure using a time-series regression of the industry's stock return on the first-difference of macro uncertainty ($\Delta v_t = v_t - v_{t-1}$) and macro growth ($g_t$):

$$R_{j,t} = const + \beta^R_{v,j}\Delta v_t + \beta^R_{g,j} g_t + error. \tag{27}$$

Similarly, for each industry j we estimate the sensitivity of its utilization growth rate to uncertainty shocks, $\beta^U_{v,j}$, using the following projection:

$$\Delta u_{j,t} = const + \beta^U_{v,j}\Delta v_t + \beta^U_{g,j} g_t + error, \tag{28}$$

where $\Delta u_{j,t}$ is the log-growth of industry j's utilization rate. The measures v_t and g_t are

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identical to those described in Section 1.2. Because v_t has a high autocorrelation, the change in macro uncertainty, Δv_t, proxies for uncertainty's innovation (similar to the approach taken by Ang, Hodrick, Xing, and Zhang (2006)). $\beta^R_{v,j}$ ($\beta^U_{v,j}$) is the return (utilization) exposure of industry j to macro uncertainty. We also estimate the standard deviation of the capacity utilization rate for each industry j, $\sigma(u_j)$.

Panel A (B) of Figure 8 shows a scatter plot of $\{(\beta^R_{v,j}, \sigma(u_j))\}_j$ ($\{(\beta^R_{v,j}, \beta^U_{v,j})\}_j$) pairs along with the linear fit. First, for almost all industries, the uncertainty risk exposure is negative, in line with existing studies. Almost all utilization elasticities to uncertainty are negative as well. Second, we find that the cross-sectional correlation between $\{\beta^R_{v,j}\}_j$ and $\{\sigma(u_j)\}_j$ is -0.45 with $p-val < 1\%$. The correlation between $\{\beta^R_{v,j}\}_j$ and $\{\beta^U_{v,j}\}_j$ is 0.39 with $p-val = .02$, confirming the predictions that utilization is key for determining uncertainty risk exposures.

5.2 Utilization and depreciation

Empirical evidence. Equation (10) of the model posits a positive and persistent link between capacity utilization and future depreciation rates. We formally examine this correlation by running a regression of future cumulative depreciation growth rate at horizon H on the current depreciation growth and the current utilization rate u_t:

$$\frac{1}{H}\Delta\delta_{t-1\to t+H-1} = const + \beta_{\delta,H}\Delta\delta_{t-1} + \beta_{u,H}u_t + error,$$

where $\Delta\delta_{t-1\to t+H-1} = \sum_{h=1}^{H}\Delta\delta_{t-1+h}$. Both the dependent and independent variables are standardized for ease of interpretation.

Table 8 shows the estimates of the slope coefficients together with the Newey-West t-statistics. In the first row of the table, the control $\Delta\delta_{t-1}$ is omitted, and the reported $\beta_{u,1}$ is equal to the correlation between $\Delta\delta_t$ and u_t. The estimated correlation is 0.52, and is economically and statistically significant. The predictive coefficient $\beta_{u,H}$ remains positive and significant at longer horizons, so that the predictive effect of utilization on future depreciation growth is persistent over time. Notably, the lagged depreciation rate remains a positive and significant predictor of its future growth controlling for the current utilization rate. Indeed, β_δ is positive and significant at least at a 10% confidence level across all the horizons. This

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Table 8: **Depreciation and utilization**

Horizon H	β_δ	t-stat	β_u	t-stat
0			0.52	[4.78]
1	0.60	[5.61]	0.45	[5.65]
3	0.31	[1.82]	0.38	[3.02]
5	0.28	[1.69]	0.23	[1.52]

The table shows the results of the regression: $\frac{1}{H}\Delta\delta_{t-1\to t+H-1} = const + \beta_{\delta,H}\Delta\delta_{t-1} + \beta_{u,H}u_t + error$. δ is private nonresidential depreciation rate. u is the capacity utilization rate. In the first row, the control $\Delta\delta_{t-1}$ is omitted. Annual data are from 1967 to 2018. Standard errors are robust and Newey West adjusted. All variables are standardized.

suggests that the current utilization rate alone does not fully capture persistent fluctuations in the depreciation rate dynamics, consistent with our modeling choice. Interestingly, when $H = 1$, the value of β_δ is 0.6 at an annual frequency, or $0.6^{1/12} = 0.96$ at the monthly frequency. This is very close to the model-implied estimate of ρ_δ.

Measurement. The BEA aims to provide an economic measure of capital depreciation. It defines depreciation as *"the decline in value due to wear and tear, obsolescence, accidental damage, and aging,"* and conceptualizes it akin to the consumption of fixed capital. Further, the economic depreciation is forward-looking, rather than historical: *"As an asset ages, its price changes because it declines in efficiency, or yields fewer productive services, in the current period and in all future periods. Depreciation reflects the present value of all such current and future changes in productive services"* (see Fraumeni (1997)).

The BEA uses geometric depreciation patterns for most asset types because they most closely align with the actual profiles of price declines in the data. To better capture the *economic* losses in asset value, the BEA employs two techniques: (a) whenever possible, it uses separate depreciation rates across different types of assets; (b) it incorporates available empirical evidence on asset prices in resale markets. Consequently, both technological progress and maintenance (utilization) changes are *implicitly* imputed into the BEA depreciation rates, via their impact on relative prices.[33]

[33] Practical challenges for measuring economic depreciation are further discussed in Hulten and Wykoff (1980); Fraumeni (1997); Giandrea, Kornfeld, Meyer, Powers, et al. (2021).

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Several economic factors can explain why changes in the utilization rate are persistently correlated with the depreciation rate, in-line with Equation (10).

(i) **Composition of capital goods.** Depreciation varies across different types of capital. For each firm, the effective depreciation rate takes an average across multiple variety of productive capital, according to their weight in firms' portfolio. Business-cycle fluctuations can induce simultaneous changes in the utilization and the composition of capital, leading to a lead-lag dependence between utilization and depreciation.

As an concrete example, according to BEA measurements, fixed capital have a lower economic depreciation than inventory capital. Assume that following an uncertainty shock, a firm stops producing new goods and ordering inputs, and sells from its existing inventory. By construction, the firm's utilization drops. Simultaneously, inventory goods are depleted, causing the weight of inventory capital to decrease, while the weight of fixed-assets increases. These relative weights change not only today (when utilization declines), but also in the future, because each weight depends on a stock variable. Consequently, a current drop in utilization would lead to a persistent decline in future depreciation.

To illustrate the plausibility of this channel in the data, we utilize the data from the BEA and construct the relative weight of equipment to inventory goods, $w_t^{relative} = \frac{w_t^{equipment}}{w_t^{equipment}+w_t^{inventory}}$. We project the cumulative relative weight growth, $\frac{1}{H}\Delta w_{t-1\to t+H-1}^{relative}$, on the first- and second-moment macro growth proxies, g_t and v_t, respectively. The results are tabulated in Table OA.1.3 of the Online Appendix. The slope coefficient on v_t ranges from 0.26 to 0.45, and remains statistically significant in all predictive horizons. Thus, macro uncertainty raises the relative weight of equipment goods at

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least 10 years ahead, inducing a persistent decline in depreciation.[34] [35]

(ii) **Capital reallocation**. According to the BEA, the depreciation rate of general equipment depends on the private sector it is used at.[36] Moreover, reallocation of equipment is not instantaneous. There is a time-to-build delay associated with shifting capital from one sector to another. These margins can generate a dynamic lead-lag relationship between the depreciation and utilization rates. On the one hand, reallocation of capital (following increased uncertainty) lowers utilization contemporaneously: the equipment cannot be fully productive while being reallocated. On the other hand, reallocation simultaneously induces a persistent and potentially permanent effect on the depreciation rate of the reallocated equipment due to sectoral fixed effects.

Notably, our model is cashless, and does not feature a storage vehicle. However, the logic above can be equally applied to instances in which capital is reallocated from a productive sector to a safe storage facility. Such reallocation results in the same interaction between utilization and future depreciation.

(iii) **Vintage effects.** To capture economic depreciation, the BEA continuously updates equipment's service life to incorporate technological progress and better maintenance.

[34] The estimates from Table OA.1.3 suggest that immediately after an uncertainty shock ($H = 1$), the relative weight of equipment rises by about 3%. If the depreciation of equipment is approximately 8% on average per annum, while the depreciation of inventory is about 20% on average, a back-of-an-envelope computation implies that the percentage fall in the aggregate depreciation rate relative to its steady state value is almost 3.5% ($= |\frac{0.08 \cdot 1.03 \cdot w_{ss}^{relative} + 0.2 \cdot (1 - 1.03 \cdot w_{ss}^{relative})}{0.08 w_{ss}^{relative} + 0.2(1 - w_{ss}^{relative})}| - 1$). This decline is, in fact, more sizable than the drop in investment following higher uncertainty, as implied by Table 2.

[35] A related narrative involves R&D capital. Assume that when uncertainty increases, firms stall research on new blueprints and generate revenue from existing product lines. This would imply that (a) utilization drops, as existing R&D-related equipment (e.g., computers and software) is underutilized; (2) At the same time, firms stop new orders of computers and software, so the relative weight of machines rises. Given that software and other R&D capital depreciate faster than machines, this would imply a persistently lower depreciation rate. We provide evidence consistent with these changes in Table OA.1.4 of the Appendix. Using BEA data, we show that uncertainty shocks positively predict the relative weight $w_t^{relative} = \frac{w_t^{equipment}}{w_t^{equipment} + w_t^{R\&D,Software}}$.

[36] To substantiate this point, Figure OA.1.3 of the Online Appendix shows a snapshot of the BEA annual depreciation estimates as of the year 2013 for general equipment. The exhibit shows that if general equipment is used in the investment sector (e.g., machine production) it has a lower depreciation than if used in the consumption sector (e.g., paper production).

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Changes in service lives can induce a persistent effect on future depreciation rates, under the realistic assumption of complementary capital vintages.[37]

For parsimony, our model focuses on a standard specification of a single sector and a single type of capital. As an aggregate representation of the economy, Equation (10) captures in a reduced-form way the rich dependence between utilization and depreciation originating from (i)–(iii) above. We leave the detailed analysis of the theoretical microfoundations of Equation (10) for a future work.

6 Conclusion

We provide novel empirical evidence for the propagation of uncertainty shocks in real and financial capital markets. We show that elevated macroeconomic uncertainty is associated with higher future capital growth. This result is quite surprising given ample empirical evidence that high uncertainty suppresses investment. To reconcile this, we document that high uncertainty leads to lower utilization and depreciation of the existing capital, and this effect dominates the adverse impact of uncertainty on investment.

We develop a parsimonious framework to account for our empirical evidence, which can be easily be incorporated into any neo-classical framework. Our economic explanation critically hinges on flexible capital utilization and persistence of capital depreciation, and provides novel insights on the implementation of precautionary savings motive in a production setting.

We further show that under our proposed mechanism, uncertainty shocks are associated with a high marginal utility of the representative agent and a decrease in equity valuations.

[37] Indeed, suppose that Equation (6) was augmented to accommodate separate capital vintages and complementary between the vintages:

$$Y_t = [(a_{t-\tau,t}K_{t-\tau})^{\chi} + (a_{t-\tau+1,t}K_{t-\tau+1}))^{\chi} ... + (u_t K_t))^{\chi}]^{\frac{\alpha}{\chi}} L_t^{1-\alpha},$$

where χ captures the elasticity of substitution across vintages. If a vintage of capital acquired τ periods ago is over-utilized, it would reduces its capital-embodied productivity for all future periods $((a'_{t-\tau,t-\tau+k}(u_t) < 0), \quad k > 1)$. This implies that all capital vintages bought afterwards would also have to be over-utilized in order to produce any unit of output, due to the complementary with the time-t vintage, whose productivity is below the steady-state. This persistence in the over-utilization of future vintages induces a persistent effect on depreciation dynamics.

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Taken together, this implies that uncertainty shocks contribute substantively to the level and variation in the equity premium. Moreover, the mechanism induces low-frequency variations in expected consumption growth. The model also provides implications for the volatility betas of equity returns and the utilization rates, which we verify in the data.

Overall, our empirical evidence and the theoretical model highlight the key role intensive margins for explaining the macroeconomic and asset-price data jointly. Our mechanism is simple to incorporate into any production model, and it gives rise to a rich interplay between time-varying risk and capital accumulation, as well as realistic implications for asset-pricing.

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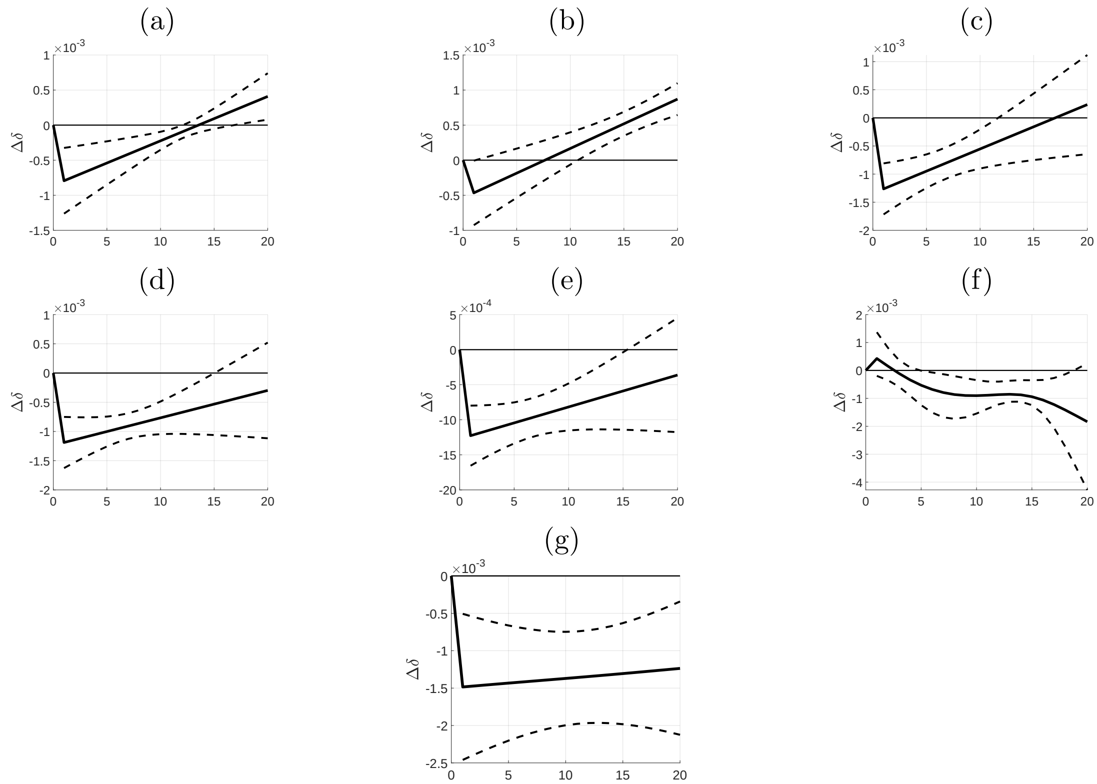
Online Appendix – For Online Publication

OA.1 Supplemental tables and figures

Figure OA.1.1: **Uncertainty shock IRF: Depreciation Response**



The figure shows the impulse responses of the growth rate of depreciation rate $\Delta\delta$ to uncertainty shocks. The impulse response functions are derived from smooth local projection of Barnichon and Brownlees (2019), and are approximated using a linear B-splines basis function expansion in the forecast horizon H. The dashed lines represent the 90% confidence interval. In Panel A, the regression includes additional controls: the market return R_m, the 3 month T-bill yield r_f, and inflation π. Panel B uses a modern sample from 1968 to 2018. In Panel C, g is TFP adjusted for utilization from Fernald (2014). In Panel D, v is the realized variance of industrial production over the last 12 months, RV. In Panel E, v is constructed using only lagged value of realized variance RV as a predictor. In Panel F, v is estimated using a GARCH(12,1) model over monthly data and averaged over the year. In panel G, we estimate v_t using a GARCH(3,1) model over annual utilization-adjusted TFP data. Annual data are from 1948 to 2018, unless noted otherwise.

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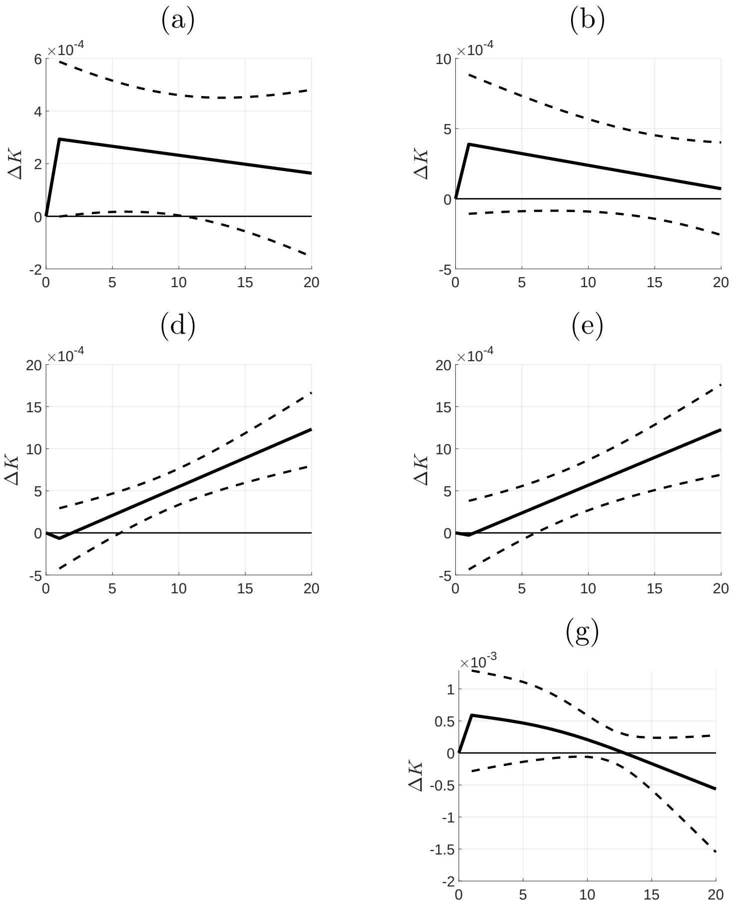
Figure OA.1.2: **Uncertainty shock IRF: Capital Response**



The figure shows the impulse responses of the growth rate of capital ΔK to uncertainty shocks. The impulse response functions are derived from smooth local projection of Barnichon and Brownlees (2019), and are approximated using a linear B-splines basis function expansion in the forecast horizon H. The dashed lines represent the 90% confidence interval. In Panel A, the regression includes additional controls: the market return R_m, the 3 month T-bill yield r_f, and inflation π. Panel B uses a modern sample from 1968 to 2018. In Panel C, g is TFP adjusted for utilization from Fernald (2014). In Panel D, v is the realized variance of industrial production over the last 12 months, RV. In Panel E, v is constructed using only lagged value of realized variance RV as a predictor. In Panel F, v is estimated using a GARCH(12,1) model over monthly data and averaged over the year. In panel G, we estimate v_t using a GARCH(3,1) model over annual utilization-adjusted TFP data. Annual data are from 1948 to 2018, unless noted otherwise.

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Table OA.1.1: **Evidence Using Uncertainty Shocks**

Horizon H	β_v	t-stat	β_g	t-stat
Panel A: $\varepsilon_{v,t}$ from specification (I)				
y = Private nonresidendtial investment rate				
1 years	-0.22	[-2.35]	0.49	[4.59]
2 years	-0.14	[-1.53]	0.51	[4.51]
3 years	-0.19	[-1.88]	0.29	[2.36]
y = Private nonresidendtial depreciation rate				
1 years	-0.15	[-1.47]	0.25	[1.94]
2 years	-0.21	[-1.95]	0.28	[2.43]
3 years	-0.22	[-2.33]	0.20	[1.87]
y = Private nonresidendtial capital				
1 years	0.15	[1.68]	0.51	[3.83]
2 years	0.17	[2.16]	0.62	[4.81]
3 years	0.16	[1.92]	0.62	[4.52]
Panel B: $\varepsilon_{v,t}$ from specification (II)				
y = Private nonresidendtial investment rate				
1 years	-0.21	[-2.32]	0.50	[4.72]
2 years	-0.16	[-1.72]	0.51	[4.63]
3 years	-0.22	[-2.18]	0.29	[2.44]
y = Private nonresidendtial depreciation rate				
1 years	-0.14	[-1.39]	0.26	[2.00]
2 years	-0.21	[-2.01]	0.29	[2.48]
3 years	-0.23	[-2.43]	0.21	[1.94]
y = Private nonresidendtial capital				
1 years	0.19	[2.00]	0.50	[3.85]
2 years	0.20	[2.41]	0.62	[4.83]
3 years	0.19	[2.10]	0.61	[4.54]
Panel C: $\varepsilon_{v,t}$ from specification (III)				
y = Private nonresidendtial investment rate				
1 years	-0.24	[-2.50]	0.53	[5.32]
2 years	-0.24	[-2.07]	0.54	[5.21]
3 years	-0.22	[-1.70]	0.32	[2.77]
y = Private nonresidendtial depreciation rate				
1 years	-0.28	[-1.72]	0.29	[2.05]
2 years	-0.36	[-1.95]	0.33	[2.46]
3 years	-0.40	[-2.15]	0.26	[2.00]
y = Private nonresidendtial capital				
1 years	0.39	[3.56]	0.46	[3.95]
2 years	0.39	[3.59]	0.58	[5.20]
3 years	0.40	[3.34]	0.57	[5.17]

The table shows the results of the regression: $\frac{1}{H}\Delta y_{t-1\to t+k-1} = const + \beta_{v,H}\varepsilon_{v,t} + \beta_{g,H}g_t + error$, where $\varepsilon_{v,t}$ is the macro uncertainty shock, and g is the real consumption growth. The level of uncertainty, v, is measured by the ex-ante volatility of industrial production under the benchmark predictors. The shock extraction varies across the panels. In panel A (specification (I)), we obtain the shock $\varepsilon_{v,t}$ from the residuals of an auto-regressive model: $v_t = const + \phi v_{t-1} + \varepsilon_{v,t}$. In panel B (specification (II)), we obtain the shock $\varepsilon_{v,t}$ from the residuals of model which controls for the lagged values of v and g: $v_t = const + \phi'[v_{t-1}, gt-1] + \varepsilon_{v,t}$. In panel C (specification (III)), we obtain the shock $\varepsilon_{v,t}$ from the residuals of model which controls for a time-trend: $v_t = const + \phi' t + \varepsilon_{v,t}$. All variables are standardized.

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Table OA.1.2: **Uncertainty, capital, and depreciation: Other robustness**

Horizon H	β_v	t-stat	β_g	t-stat
Panel A: Nonresidential equipment				
$y = \delta$				
1 years	-0.42	[-3.56]	0.40	[4.83]
2 years	-0.46	[-4.11]	0.31	[3.74]
3 years	-0.48	[-4.25]	0.16	[1.78]
$y = K$				
1 years	0.16	[1.26]	0.37	[2.44]
2 years	0.16	[1.09]	0.49	[3.47]
3 years	0.13	[0.86]	0.47	[3.16]
Panel B: t to $t+H$ growth rate				
$y = \delta$				
1 years	-0.32	[-2.17]	0.25	[2.44]
2 years	-0.33	[-2.34]	0.12	[1.32]
3 years	-0.36	[-2.42]	0.02	[0.25]
$y = K$				
1 years	0.24	[2.84]	0.69	[6.71]
2 years	0.24	[2.36]	0.63	[5.48]
3 years	0.25	[2.25]	0.55	[4.25]
Panel C: v is the realized variance of industrial production				
$y = \delta$				
1 years	-0.24	[-2.09]	0.25	[1.95]
2 years	-0.31	[-2.06]	0.29	[2.44]
3 years	-0.32	[-2.33]	0.21	[1.89]
$y = K$				
1 years	0.11	[1.16]	0.50	[3.69]
2 years	0.10	[1.14]	0.61	[4.61]
3 years	0.08	[0.83]	0.60	[4.35]
Panel D: v is GARCH volatility of TFP				
$y = \delta$				
1 years	-0.34	[-2.41]	0.33	[2.68]
2 years	-0.39	[-2.51]	0.38	[3.24]
3 years	-0.39	[-2.52]	0.30	[2.75]
$y = K$				
1 years	0.13	[1.20]	0.47	[3.39]
2 years	0.14	[1.42]	0.58	[4.34]
3 years	0.15	[1.45]	0.57	[4.20]
Panel E: v is JLN financial uncertainty				
$y = \delta$				
1 years	0.04	[0.24]	0.41	[2.76]
2 years	-0.18	[-1.04]	0.44	[3.07]
3 years	-0.29	[-1.74]	0.31	[2.24]
$y = K$				
1 years	0.43	[4.48]	0.52	[3.68]
2 years	0.30	[2.84]	0.62	[4.49]
3 years	0.17	[1.81]	0.61	[4.65]
Panel F: v is EPU policy uncertainty				
$y = \delta_t$				
1 years	-0.13	[-0.92]	0.51	[3.08]
2 years	-0.24	[-1.66]	0.36	[2.23]
3 years	-0.25	[-2.45]	0.14	[0.85]
$y = K_t$				
1 years	0.14	[1.05]	0.73	[5.59]
2 years	0.04	[0.27]	0.73	[7.77]
3 years	0.06	[-0.43]	0.66	[8.28]

The table shows the results of the regression: $\frac{1}{H}\Delta y_{t-1\to t+k-1} = const + \beta_{v,H} v_t + \beta_{g,H} g_t + error$, where y is either is private nonresidential depreciation rate δ, or the stock of nonresidential capital K. v is macro uncertainty, measured by the ex-ante volatility of industrial production under the benchmark predictors, and g is the real consumption growth, unless noted otherwise. In Panel A, the depreciation and capital stock are of private nonresidential equipment only. In Panel B, the dependent variable is $\frac{1}{H}\Delta y_{t\to t+k}$. In Panel C, v is the realized variance of industrial production over the last 12 months, RV. In Panel D, v is based on GARCH model of utilization adjusted TFP. In Panel E (F), v is financial (policy) uncertainty of Ludvigson et al. (2021) (Baker et al. (2016)).

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Table OA.1.3: **Uncertainty and the relative weight of equipment to inventory**

Horizon H	β_v	t-stat	β_g	t-stat
1 years	0.45	[3.79]	-0.03	[-0.35]
3 years	0.26	[2.52]	0.26	[1.98]
5 years	0.33	[3.08]	0.26	[1.94]
7 years	0.31	[1.89]	0.37	[3.32]
9 years	0.43	[2.36]	0.23	[1.86]
10 years	0.38	[1.89]	0.20	[1.74]

The table shows the results of the regression: $\frac{1}{H}\Delta y_{t-1\rightarrow t+k-1} = const + \beta_{v,H} v_t + \beta_{g,H} g_t + error$, where y is the relative weight of equipment to inventory goods, $w_t^{relative} = \frac{w_t^{equipment}}{w_t^{equipment} + w_t^{inventory}}$ from the BEA. v is macro uncertainty, measured by the ex-ante volatility of industrial production. g is real consumption growth. Annual data are 1948 to 2018. Standard errors are robust and Newey West adjusted. All variables are standardized.

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Table OA.1.4: **Uncertainty and the relative weight of equipment to R&D and software**

Horizon H	β_v	t-stat	β_g	t-stat
1 years	0.23	[2.56]	0.01	[0.07]
3 years	0.22	[2.62]	-0.11	[-0.70]
5 years	0.30	[3.61]	-0.12	[-1.02]
7 years	0.41	[4.35]	-0.03	[-0.26]
9 years	0.55	[5.40]	0.09	[0.98]
10 years	0.54	[5.23]	0.14	[1.42]

The table shows the results of the regression: $\frac{1}{H}\Delta y_{t-1\to t+k-1} = const + \beta_{v,H} v_t + \beta_{g,H} g_t + error$, where y is the relative weight of equipment to R&D and software capital, $w_t^{relative} = \frac{w_t^{equipment}}{w_t^{equipment} + w_t^{R\&D,Software}}$ from the BEA. v is macro uncertainty, measured by the ex-ante volatility of industrial production. g is real consumption growth. Annual data are 1948 to 2018. Standard errors are robust and Newey West adjusted. All variables are standardized.

Figure OA.1.3: **General equipment depreciation rate in 2013**

BEA Rates of Depreciation, Service Lives, Declining-Balance Rates, and Hulten-Wykoff Categories--Table Continues

Type of Asset	Rate of depreciation	Service life	Declining balance rate	Hulten-Wykoff category/1/
General industrial, including materials handling equipment:				
Nonmanufacturing industries	0.1072	16	1.715	A
Durable manufacturing:				
Wood products	0.1429	12	1.715	A
Nonmetallic mineral products	0.0903	19	1.715	A
Primary metals	0.0635	27	1.715	A
Fabricated metal products	0.0715	24	1.715	A
Machinery	0.0686	25	1.715	A
Computer and electronic products	0.1225	14	1.715	A
Electronic equipment, appliances, and components	0.1225	14	1.715	A
Motor vehicles, bodies and trailers, and parts	0.1225	14	1.715	A
Other transportation equipment	0.1009	17	1.715	A
Furniture and related products	0.1225	14	1.715	A
Miscellaneous manufacturing:				
Medical equipment and supplies	0.1225	14	1.715	A
Other	0.1009	17	1.715	A
Nondurable manufacturing:				
Food and beverage and tobacco products:				
Food	0.0858	20	1.715	A
Beverage and tobacco product	0.0817	21	1.715	A
Textile and textile product mills	0.1072	16	1.715	A
Apparel and leather and allied products	0.1143	15	1.715	A
Paper products	0.1072	16	1.715	A
Printing and related support activities	0.1143	15	1.715	A
Petroleum and coal products	0.0780	22	1.715	A
Chemical	0.1072	16	1.715	A

The figure shows the example of depreciation rates of general equipment which depend on the sector of usage. BEA table for 2013 year.

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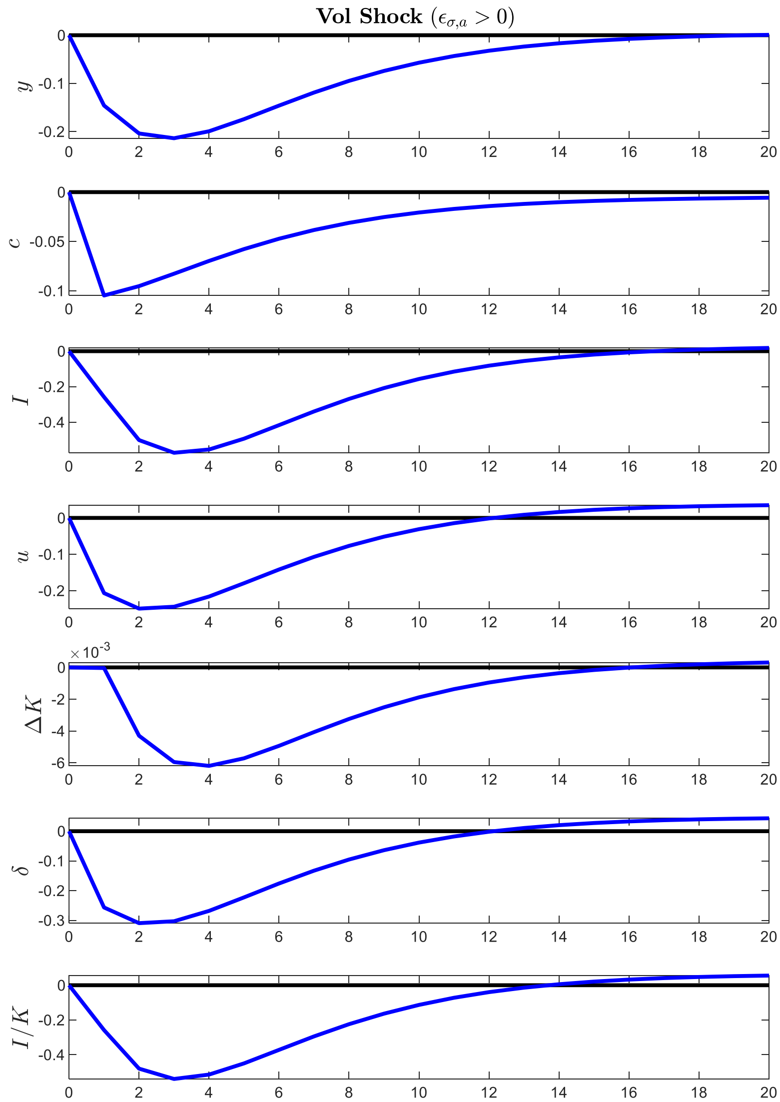
Figure OA.1.4: **Basu and Bundick (2017): Deprecation, and capital growth**



The figure shows the replicated impulse responses to uncertainty shocks under the benchmark calibration of Basu and Bundick (2017) model. The vertical axis represents percent deviation from the steady state value. The first three IRFs for output y, consumption c , and investment I, are reported by authors in Figure 3. The other IRFs for utilization u, capital growth ΔK, depreciation rate δ, and investment rate I/K are based on the replication code, extended to accommodate these IRFs.

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OA.2 Micro-level Evidence

Our benchmark analysis focuses on aggregate uncertainty and its relation to macro variables. Yet, for robustness, we show that the main facts hold at the firm-level using micro-level measures of uncertainty. Figure OA.2.5 shows the outcome of the following local projection:

$$y_{t+H,i} = \alpha_{i(H)} + \alpha_{t(H)} + \beta_{v(H)} v_{i,t} + \beta_{g(H)} g_{i,t} + \beta'_{control(H)} \omega_t + error,$$

where $v_{i,t}$ is a proxy for firm i's uncertainty at time t, as measured by its realized volatility of daily stock returns over the last year, $g_{i,t}$ is a proxy for firm i's first-moment shock at time t, as measured by its realized return over the last year, and additional controls ω_t include lagged investment rate, capital growth and depreciation rate. The independent variable y is either capital growth (implied from $PPENT$) or depreciation rate (implied from $PPENT$ and $CAPX$) at different horizons. Whenever significant, the impact of micro-level uncertainty on depreciation (capital growth) is negative (positive).

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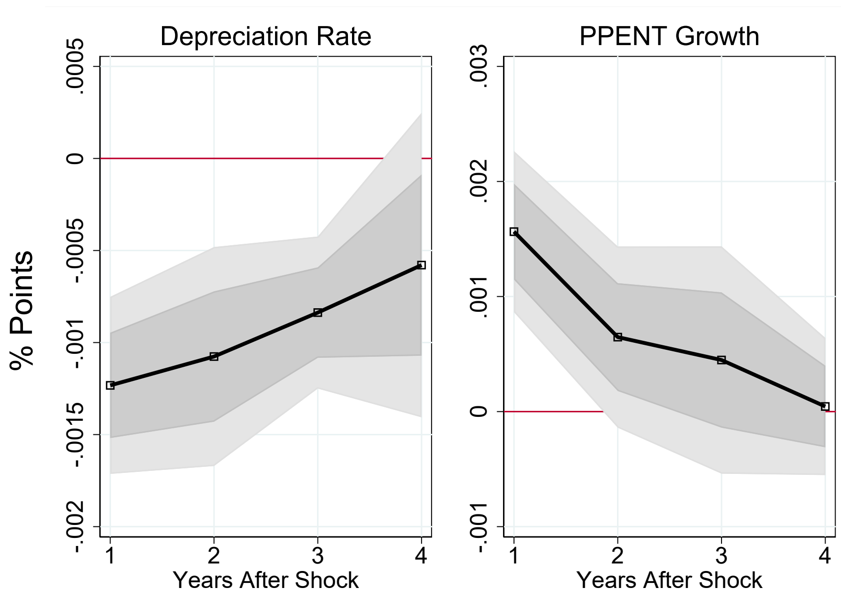
Figure OA.2.5: **Uncertainty shocks IRF: Micro-level, Compustat evidence**



The figure shows the impulse responses of the growth rate of firm-level depreciation rate and capital stock to firm-level uncertainty shocks. The impulse response functions correspond to $\beta_{v,H}$ coefficients in smooth local projection of Barnichon and Brownlees (2019) of the form: $y_{t+H,i} = \alpha_{i,H} + \alpha_{t,H} + \beta_{v,H} v_{i,t} + \beta_{g,H} g_{i,t} + \beta'_{control,H} Y_t + error$. $v_{i,t}$ is a proxy for firm i's uncertainty at time t, as measured by the realized volatility of daily stock returns over the last year, $g_{i,t}$ is a proxy for firm i's first-moment shock at time t, as measured by its realized return over the last year, and additional controls Y_t include lagged investment rate, capital growth and depreciation rate. Annual observations from from 1970-2018.

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OA.3 Comparison to the New-Keynesian model

In this section, we present an augmented model that accommodates monopolistic competition and nominal rigidity.

The household side of the economy is identical to that described in Section 2. Unlike the perfect competition model, the economy is populated by a mass of differentiated intermediate good producers, indexed by $m \in [0,1]$. The output of an intermediate good producer at time t of variety m is denoted by $y_t(m)$ and its price is $p_t(m)$.

Aggregator. An aggregator converts the intermediate goods into a final composite layer good, Y_t, using a CES production function:

$$Y_t = \left[\int_0^1 y_t(m)^{\frac{\theta-1}{\theta}} dm\right]^{\frac{\theta}{\theta-1}}. \tag{29}$$

For any finite θ, the intermediate goods are not perfect substitutes, and producers possess some amount of monopolistic power.

The aggregator faces perfect competition in the product market. It solves:

$$\max_{\{y_t(m)\}} \quad P_t Y_t - \int_0^1 p_t(m) y_t(m) dm \quad \text{s.t equation (29)}.$$

It follows that the price index is given by $P_t = \left[\int_0^1 p_t(m)^{1-\theta} dm\right]^{\frac{1}{1-\theta}}$, and the demand schedule for each intermediate good producer of variety m is $\left[\frac{p_t(m)}{P_t}\right]^{-\theta} Y_t$.

The aggregator supplies final goods used for either consumption or investment by the intermediate good producers.

Intermediate good producers. The intermediate good producer of variety m faces the same capital accumulation and production technology as described in Section 2.1. It owns its capital stock, $K_t(m)$, which depreciates at rate $\delta_t(m)$, and it hires labor from the household. It has an additional degree of freedom and can optimally select its nominal output price.

The real dividend of an intermediate good producer of variety m, $d_t(m)/P_t$, is given by:

$$d_t(m)/P_t = \left[\frac{p_t(m)}{P_t}\right]^{1-\theta} Y_t - I_t - W_t/P_t \cdot L_t(m) - \phi_P/2 \left(\frac{p_t(m)}{\Pi p_{t-1}(m)} - 1\right)^2 Y_t, \tag{30}$$

where ϕ_P captures the degree of nominal rigidity as in Rotemberg (1982). Each intermediate good producer chooses its output price, optimal hiring, utilization rate, and investment, to

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maximize its market value, taking as given wages W_t, the price index P_t, and the stochastic discount factor of the household $M_{t,t+1}$. Specifically, each firm maximizes:

$$V_t(m) = \max_{\{L_s(m)\, p_s(m),\, K_{s+1}(m)\, u_s(m)\}} \quad E_t \sum_{s=t}^{\infty} M_{t,s}(d_s(m)/P_s) \tag{31}$$

s.t.

$$\left[\frac{p_t(m)}{P_t}\right]^{-\theta} Y_t \leq A_t^{1-\alpha}(u_t(m)K_t(m))^{\alpha} L_t(m)^{1-\alpha}$$

$$K_{t+1}(m) = (1-\delta_t(m))K_t(m) + \phi\left(\frac{I_t(m)}{K_t(m)}\right)K_t(m)$$

$$\delta_t(m) = (1-\rho_\delta)\delta_0 + \rho_\delta \delta_{t-1}(m) + \varepsilon_\delta(u_t(m)),$$

where $\varepsilon_\delta(u_t(m))$ is given by Eq (9).

Monetary Policy. A monetary authority sets the nominal interest rate r_t according to the following rule:

$$r_t = r_{ss} + \rho_\pi(\pi_t - \pi_{ss}) + \rho_y(\Delta y_t - \Delta y_{ss}),$$

where $r_t = \log(R_t)$, $\pi_t = \log(\Pi_t) = \log(P_t/P_{t-1})$, and $\Delta y = \log(Y_t/Y_{t-1})$. π_{ss} and Δy_{ss} are the steady-state log inflation and log output growth, respectively.

Aggregate productivity. We consider two separate dynamics for aggregate productivity. The first case corresponds to permanent productivity shocks to A_{t+1}:

$$\Delta a_{t+1} = \mu + e^{\sigma_{a,t}}\tilde{\sigma}_a \varepsilon_{a,t+1}.$$

The second case corresponds to transitory productivity shocks to A_{t+1}:

$$A_{t+1} = \mu^{t+1}\exp(e^{\sigma_{a,t}}\tilde{\sigma}_a \varepsilon_{a,t+1}).$$

In both cases, the stochastic volatility $\sigma_{a,t}$ follows the dynamics described in equation (18).

Market clearing and equilibrium. The market clearing conditions of the labor markets, and the goods markets are modified as follows:

$$\int_0^1 L_t(m)dm = 1, \quad \int_0^1 I_t(m)dm + C_t = Y_t.$$

Equilibrium consists of prices, labor, utilization, and capital allocations such that (i) taking prices and wages as given, the household's allocation maximizes (13), and firms' allocations solve (31); (ii) all markets clear; (iii) we are interested in a symmetric equilibrium in which

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$K_t(m) = K_t$, $u_t(m) = u_t$, $L_t(m) = L_t$, and $p_t(m) = p_t$, for all $m \in [0, 1]$.

Calibration. All model parameters are identical to those specified in Section 2.6, with the following additions and modifications: (i) following Basu and Bundick (2017) we set $\rho_\pi = 1.5$, $\rho_y = 0.2$, $\theta = 6$, $\phi_P = 100$; (ii) $\tilde{\sigma}_a = \sqrt{\sigma_a^2/(1-\rho_a^2}$ (the values of σ_a and ρ_a are identical to Table 5).

Impulse responses. Figures OA.3.6 and OA.3.7 show the model-implied uncertainty impulse responses under the case of permanent and transitory productivity shocks, respectively. We obtain the following results:

(1) With either permanent or transitory productivity shocks, our mechanism of flexible utilization and persistent depreciation alone (i.e., $\rho_\delta = 0.99$ but $\phi_P = 0$) is sufficient to induce comovement between consumption, investment and output following an uncertainty shock. All real quantities decrease in the presence of fixed but positive markups.

(2) Under permanent productivity shocks, time-varying markups alone (i.e., $\rho_\delta = 0$ but $\phi_P = 100$) reduce investment compared to the case of fixed markups ($\phi_P = 0$). However, quantitatively, investment still rises in response to an uncertainty shock, despite utilizing the same values for θ and ϕ_P as in Basu and Bundick (2017).

(3) Under permanent productivity shocks, when we combine our channel ($\rho_\delta = 0.99$) with the time-varying markup channel ($\phi_P = 100$) the drop in investment, consumption, and output is only slightly amplified compared to the case of persistent depreciation and fixed markups. About 95% of the drop in investment is due to the persistent depreciation, while 5% is due to the rise in markups.

(4) Under transitory productivity shocks, the time-varying markup channel alone (i.e., $\rho_\delta = 0$ but $\phi_P = 100$) is sufficiently strong as to drop consumption, investment and output, following an uncertainty shock. This is consistent with the results of Basu and Bundick (2017), that study the time-varying volatility of mean-reverting shocks. When time-varying markups are combined with persistent depreciation (i.e., $\rho_\delta = 0.99$

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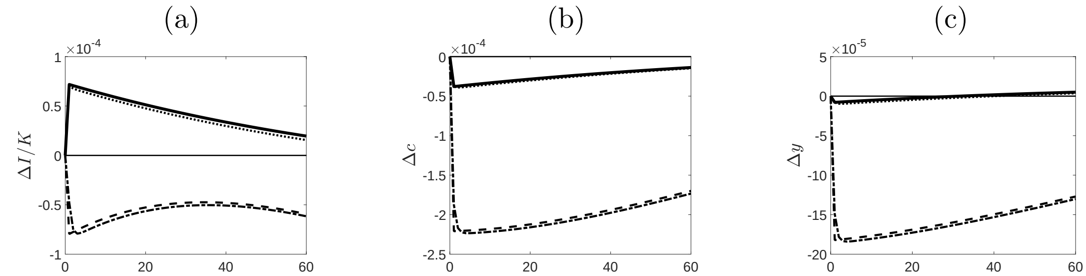
Figure OA.3.6: **Uncertainty shocks IRF: New-Keynesian model with permanent productivity shocks**



The figure shows model-implied uncertainty impulse responses to (a) investment rate $\Delta I/K$, (b) consumption c, and (c) output y. We consider calibrations with no persistent depreciation and no price stickiness ($\rho_\delta = 0$, $\phi_P = 0$, solid line); persistent depreciation but no price stickiness ($\rho_\delta = 0.99$, $\phi_P = 0$, dashed line); no persistent depreciation but with price stickiness ($\rho_\delta = 0$, $\phi_P = 100$, dotted line); persistent depreciation and price stickiness ($\rho_\delta = 0.99$, $\phi_P = 100$, dotted-dashed line). In all specifications, utilization is flexible and the average markups are identical. The productivity shocks have a permanent effect on productivity's level ($\Delta a_{t+1} = \mu + e^{\sigma_{a,t}}\sigma_a\varepsilon_{a,t+1}$). All growth impulse responses are cumulative.

and $\phi_P = 100$), about 60% of the drop in consumption and output is due to time-varying markups, and 40% of the drop is due to the depreciation dynamics. Thus, our economic channel provides a significant amplification to the economic channel of Basu and Bundick (2017).

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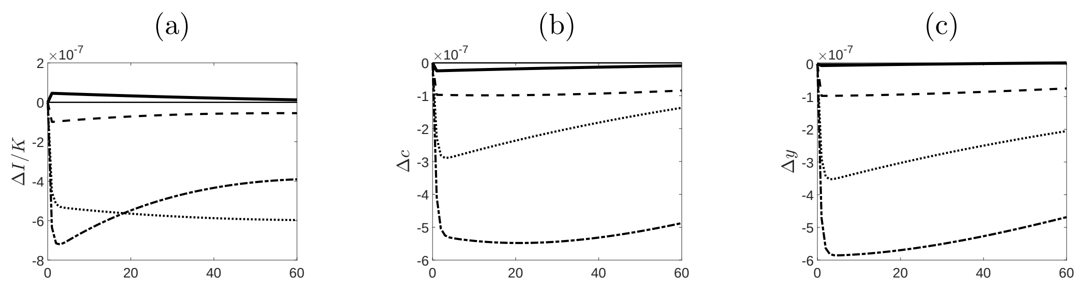
Figure OA.3.7: **Uncertainty shocks IRF: New-Keynesian model with transitory productivity shocks**



The figure shows model-implied uncertainty impulse responses to (a) investment rate $\Delta I/K$, (b) consumption c, and (c) output y. We consider calibrations with no persistent depreciation and no price stickiness ($\rho_\delta = 0$, $\phi_P = 0$, solid line); persistent depreciation but no price stickiness ($\rho_\delta = 0.99$, $\phi_P = 0$, dashed line); no persistent depreciation but with price stickiness ($\rho_\delta = 0$, $\phi_P = 100$, dotted line); persistent depreciation and price stickiness ($\rho_\delta = 0.99$, $\phi_P = 100$, dotted-dashed line). In all specifications, utilization is flexible and the average markups are identical. The productivity shocks have a permanent effect on productivity's level ($A_{t+1} = \mu^{t+1} \exp(e^{\sigma_{a,t}} \sigma_a \varepsilon_{a,t+1})$). All growth impulse responses are cumulative.

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