Uncertainty, Risk, and Capital Growth [*]

Gill Segal and Ivan Shaliastovich

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Abstract

We present a novel finding that high macroeconomic uncertainty is associated with greater accumulation of physical capital, despite a reduction in investment. To reconcile this seemingly contradictory evidence, we show that high uncertainty predicts a persistent decrease in utilization and depreciation of capital, which quantitatively dominates the investment slowdown. We construct and estimate a general-equilibrium model to explain our new findings alongside existing evidence on uncertainty, economic growth, and asset prices. In the model, precautionary saving is achieved by lowering utilization, instead of increasing investment. Lower utilization persistently decreases depreciation, conserving capital for the future, and simultaneously discourages new investment. We further show the importance of our mechanism to generate a negative impact of uncertainty shocks in an extended New-Keynesian framework.

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[*]Segal: (Gill_Segal@kenan-flagler.unc.edu), Kenan-Flagler Business School, University of North Carolina at Chapel Hill; Shaliastovich: (ivan.shaliastovich@wisc.edu), Wisconsin School of Business, University of Wisconsin - Madison. We thank Ravi Bansal, Adrien d'Avernas, Lorenzo Garlappi, Naveen Gondhi, Philipp Illeditsch, Christian Opp, Sergio Salgado, Lukas Schmid, Fernando Zapatero, and conference and seminar participants at Society of Financial Econometrics Meeting 2021, Stanford Institute for Theoretical Economics (SITE) - Macro Finance and Computation 2021, 8^{th} SAFE Asset Pricing Workshop, European Finance Association Meeting 2021, Triangle Macro-Finance Workshop, 2022 American Finance Association (AFA) Meeting, 2022 Midwest Finance Association (MFA) Meeting, SFS Cavalcade 2022, ITAM finance conference 2022, 2022 China International Conference in Finance, Johns Hopkins University, IDC, Chinese University of Hong Kong, City University of Hong Kong, Hong Kong University of Science and Technology for their comments.

1 Introduction

Empirical evidence suggests that high macroeconomic uncertainty has an adverse effect on real economy and financial markets. Indeed, an increase in aggregate uncertainty is commonly associated with a business cycle trough and a persistent decline in aggregate consumption, investment, and output. At the same time, firm valuations decline while the market risk and risk premia increase. These findings have spurred a large and growing literature which studies the dynamic interactions between uncertainty, real economy, and asset markets.

In this study, we present novel empirical evidence that challenges the existing views on uncertainty shocks in capital markets. We document that both in the aggregate time-series and the cross-section, high uncertainty is associated with *greater accumulation* of future capital, despite of having a negative effect on investment. This fundamental result is surprising at 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 be affected by uncertainty shocks, which would reconcile the joint evolution of capital and investment dynamics. Indeed, we find that both investment and the capital depreciation rate decrease following a rise in aggregate economic uncertainty. The decline in depreciation cushions the investment slowdown, and is quantitatively large enough to induce a build-up in the capital stock at times of high uncertainty.

To shed light on the economic origin of the fluctuations in the depreciation rate, we show that aggregate uncertainty leads to a sharp decline in the utilization of installed capital, inducing a persistent negative effect on depreciation. Collectively, our evidence highlights a rich pattern of propagation of uncertainty shocks in capital dynamics, which, we argue, is a novel contribution to the literature.

We next develop and estimate an economic model to reconcile the novel empirical findings alongside the existing evidence on the relationship between uncertainty, economic growth, and asset prices. Our model mechanism critically relies on time-varying and persistent fluctuations in the depreciation rate, driven by capacity utilization. Specifically, we allow utilization to have a long-lasting impact on future depreciation. This channel is new to the literature and is motivated by empirical and conceptual considerations. In the data, the capital depreciation rate is significantly more persistent than the utilization rate, and exhibits much more slowly-decaying response to economic shocks. Conceptually, we discuss possible microfoundations for the persistent link between the current utilization rate and future depreciation rates, which align with the BEA's measurement of economic depreciation. These microfoundations include reallocation of capital across sectors, heterogeneity in depreciation rates across different types of capital, or complementarity of utilization across capital vintages.

We incorporate this empirically-driven augmented specification for the capital accumulation dynamics into a parsimonious real business cycle model. Incorporating these dynamics changes the qualitative and quantitative implications of the canonical model. A key insight of the model is that lower utilization substitutes higher investment for precautionary saving, with the benefit of avoiding costs associated with new capital installation. Specifically, when uncertainty increases, the firm has incentives to build up capital to create a buffer against large downside moves in future productivity. It can do so by lowering the utilization rate of the capital already installed. Under-utilization of capital decreases its depreciation rate and preserves it for future use, consistent with our novel empirical evidence. While a decrease in the equilibrium risk-free rates operates to raise investment, a persistent drop in utilization lowers the expected marginal product of capital and discourages investment. Quantitatively, we estimate that the effect of lower effective productivity (via lower utilization) dominates the effect of precautionary savings on new investments, and investment declines. Nonetheless, the future capital grows via the depreciation channel. Finally, lower utilization decreases the level of current and future output. In the model, the decline in output is larger than the decline in investment, and as a result, consumption decreases as well.

The utilization-induced channel for depressing investment following higher uncertainty differs from other mechanisms proposed in the literature, such as real-options or time-varying markups. In particular, our proposed channel can work under perfect-competition, and without non-convex adjustment costs. As later discussed under related literature, existing frameworks with uncertainty risks either fail to eliminate the precautionary saving effect on investment (ipso-facto, leading to a divergence of investment from consumption), or alternatively, depress both investment and future capital growth in response to uncertainty, in contrast to our novel finding.

To further highlight the distinction between our proposed mechanism and existing channels that induce uncertainty-driven recessions, we consider an extension of the model which incorporates flexible utilization and persistent depreciation dynamics into a New-Keynesian model featuring monopolistic competition and nominal price rigidity. We show that our novel channel remains quantitatively important. 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 effect of uncertainty shocks on real variables above and beyond the effect induced by countercyclical markups.

While our framework is not directly targeting asset-price data, it is able to produce a sizable risk premium on a levered equity claim. In the model the firm's investment rate and stock prices comove, a standard implication of q-theory. When utilization is fixed, uncertainty shocks increase investment, which leads to a counterfactual positive risk exposure of the market portfolio to uncertainty shocks. However, when utilization is flexible, uncertainty decreases the firm's investment and valuation, so that the uncertainty risk exposure turns negative. With a preference for early resolution of uncertainty, uncertainty shocks increase the marginal utility, and thus have a negative market price of risk. Overall, uncertainty shocks contribute positively to the model-implied equity premium, and explain about a quarter of its magnitude.

We further examine additional properties of the model in the cross-section of industry asset returns. In the model, firms with a more volatile utilization rate, or with utilization rates more exposed to macroeconomic uncertainty, exhibit more negative return exposure to uncertainty. We confirm these model predictions empirically using the cross-sectional data on manufacturing, mining, and utility industries.

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), Dixit, Dixit, and Pindyck (1994), and recently Bloom (2009) and Bloom, Floetotto, Jaimovich, Saporta-Eksten, and Terry (2018) use a real option channel (or "bad news" principle) to explain why uncertainty suppresses investment. Importantly, the positive effect of uncertainty on the capital stock which we document in this study differs from the investment overshoot effect predicted by real option models, as capital rises despite of a *contemporaneous* decline in investment. The study of Fernández-Villaverde, Guerrón-Quintana, Rubio-Ramirez, and Uribe (2011) examines uncertainty in the context of an open economy, showing that volatility lowers domestic investment. Other papers suggest that uncertainty increases firms' cost of capital, or credit spreads, making investment more costly (see, e.g., Christiano, Motto, and Rostagno, 2010; Gilchrist, Sim, and Zakrajšek, 2014; Arellano, Bai, and Kehoe, 2019). Di Tella and Hall (2021) rely on a model that features uninsurable idiosyncratic risk and predetermined labor. The covariance between firms' marginal product of labor and the households' SDF creates a risk premium wedge that suppresses investment and hiring. We differ from these studies in two ways. First, in all these studies, with an exception of Di Tella and Hall (2021), uncertainty decreases investment but does not generate positive contemporaneous comovement between consumption and investment. Second, all of the studies above feature a constant depreciation rate, and thus, cannot account for our new evidence on the response of depreciation rate to uncertainty shock, or for the wedge between investment and capital growth following higher uncertainty. [1]

Related, the models of Fernández-Villaverde, Guerrón-Quintana, Kuester, and Rubio-Ramírez (2015) and Basu and Bundick (2017) rely on a New Keynesian framework that features monopolistic competition and sticky prices to show that both consumption and investment drop in response to uncertainty shocks. The mechanism in both papers is similar: uncertainty increases firms' markups, which has a rationing effect on production. Importantly, and consistent with other New Keynesian models, both studies feature flexible utilization. However, these studies do not incorporate persistent depreciation, so that the effect of changing utilization only impacts the contemporaneous depreciation rate. Flexible utilization helps to quantitatively extend the duration of price stickiness and magnify the decline in investment; however,

[1] Bloom (2009) documents that uncertainty shocks lead to an investment overshoot in the long-run. This result, however, is distinct from increase in the capital growth documented in our study. In Bloom (2009), the model-implied capital growth increases because future investment rises, while in our model it increases despite of the investment slowdown due to a fall in depreciation.

without persistent depreciation, this channel cannot reconcile our novel facts.[2]

More broadly, following Jaimovich and Rebelo (2009), the RBC literature has proposed flexible utilization as a key ingredient to overcome the comovement problem of macro variables with respect to *first-moment* news shocks (see, e.g., Barro and King (1984)). Our paper complements this idea by showing that utilization, coupled with persistent depreciation, can generate comovement with respect to *second-moment* productivity shocks, and reverse the precautionary saving effect on investment. Our economic mechanism is thus distinct from the existing literature. Specifically, Jaimovich and Rebelo (2009) show that first-moment new shocks increase future investment, leading to higher investment today in the presence of adjustment costs. In turn, this reduces the value of installed capital, allowing contemporaneous capacity utilization to rise, thereby increasing output. By contrast, in our model, a positive uncertainty shock drops expected utilization as a way to save. This is equivalent to a negative first moment TFP shock that suppresses contemporaneous investment. The substitution between new investment and lower utilization helps to build up capital, while endogenously economizing on adjustment costs.[3]

In relation to asset prices, in contrast to the endowment economies in which high uncertainty increases equity risk premium[4], in a standard production setting uncertainty shocks lower the equity premium, and increase stock prices. We show that under our model ingredients, uncertainty shocks decrease stock prices, increase the marginal utility, and contribute positively to risk premia. Thus, our channel complements other production-based asset pricing models in which discount rate shocks suppress investment and raise equity premium, relying on resource reallocation (e.g., Gao,

[2]We replicate the model of Basu and Bundick (2017) and derive the impulse responses of depreciation and capital growth to uncertainty shocks. As shown in Figure OA.1.3 in the Online Appendix, under the estimated parameters of Basu and Bundick (2017), the model-implied utilization and depreciation drop following an uncertainty shock, and investment declines by a stronger amount, suggesting that future capital growth falls, in contrast to our empirical evidence.

[3]The study of Jaimovich and Rebelo (2009) also features investment-specific technology shocks (IST) which effectively changes the relative price of investment goods or capital vintages. Importantly, introducing IST shocks cannot on its own account for the divergence between capital growth and investment following higher uncertainty. To see this, assume that uncertainty raises the relative price of capital, and consequently, the value of capital appreciates (in line with the data). The same relative price simultaneously scales investment expenditures, and consequently, should induce investment to rise as well (in contrast to the data).

[4]See, e.g., Bansal and Yaron, 2004; Boguth and Kuehn, 2013; Croce, Lettau, and Ludvigson, 2015; Johannes, Lochstoer, and Mou, 2016; Ai and Kiku, 2016, among many others

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 investment risk (e.g., Dou (2017)), or multiple sectors and uncertainties (e.g., Segal, Shaliastovich, and Yaron (2015) and Segal (2019)).[5]

Finally, several recent studies question the role of macro uncertainty to induce recessions (see, e.g., Berger, Dew-Becker, and Giglio, 2020; Ludvigson, Ma, and Ng, 2021). In particular, Ludvigson et al. (2021) use a SVAR methodology to show that macro uncertainty only deepens a decline in industrial production followed by negative first-moment shocks, but does not cause a decrease in industrial production on its own. Our findings that uncertainty has a negative effect on investment and positive on the future stock of capital can potentially shed light on the ambiguous role of macro uncertainty for aggregate economic indices.

The rest of the paper is organized as follows. We establish novel empirical facts connecting macro uncertainty to depreciation and capital growth in Section 2. We present our model with uncertainty shocks, flexible utilization, and persistent depreciation in Section 3. In Section 4 we show that the model is capable of producing uncertainty-induced real recessions that are consistent with the new empirical evidence. In Section 5 we discuss the implications of uncertainty shocks for financial markets from the lens of the model. We provide concluding remarks in Section 6.

2 Empirical evidence

We examine the empirical relation between macroeconomic uncertainty and three components of capital accumulation: the depreciation rate, the investment rate, and capital growth. We establish our key empirical finding that an increase in uncertainty is associated with a lower depreciation rate and higher future capital growth, in spite of lower investment rates. We further document that high capital utilization is associated with a persistent increase in capital depreciation.

[5]Our paper also related to studies that incorporate flexible utilization in asset-pricing (see, e.g., Garlappi and Song, 2017; Grigoris and Segal, 2022). These studies do not consider the interaction between utilization and second-moment shocks.

2.1 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 comes from the San Francisco Fed, following the methodology of Fernald (2014). Real consumption, defined as non-durables and services, is from the Bureau of Economic Analysis (BEA) National Income and Product Accounts Tables. We obtain data on chain-type quantity indices for the net stock of fixed assets, depreciation for fixed assets, and investment in fixed assets from BEA Fixed Assets Accounts Tables. All fixed asset indices are chained to the year 2012 (i.e., indices equal to 100 at that year). We convert these indices to real dollars by multiplying them by their respective dollar amount as of 2012. In our benchmark results we focus on the depreciation and investment of private non-residential capital. We construct the depreciation rate as the dollar depreciation of year t divided by the stock of capital of year $t-1$. Similarly, the investment rate is constructed by dividing the dollar investment amount of year t by the dollar amount of capital stock in year $t-1$.

Important for our analysis, the BEA aims to provide an economic, rather than an accounting, 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 as 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)). In particular, technological progress and better maintenance which impact the future service life of equipment, are continuously embedded into the depreciation rates.

To measure the depreciation dynamics, the BEA incorporates available empirical evidence of used asset prices in resale markets, based on numerous studies conducted over multiple decades. It uses geometric depreciation patterns for most asset types because they most closely align with the actual profiles of price declines in the data. Further, to better capture the economic patterns of the asset value loss, whenever possible, the BEA uses separate depreciation rates across different types of the asset and different industries.[6]. In Section 3.1 we discussion how these measurement methodologies reconcile our empirical findings.

Finally, we obtain asset price data from the Center for Research in Security Prices (CRSP). We measure the nominal risk free rate as the 3-month T-bill yield, and the market return by the value weighted CRSP annual return. Based on the availability of productivity and fixed assets data, all variables are measured at an annual frequency, covering a postwar sample from 1948 to 2018. The only exception is data on capacity utilization rate, which are available from 1968 to 2018.

2.2 Measuring macroeconomic uncertainty

The macroeconomic uncertainty, denoted by v_t, is aimed to capture the predictable variation in a macroeconomic 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 associated with shocks to the underlying growth 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. To construct the predictive component, we project the logarithm of time $t+1$ realized variance on a set of time t predictors, Γ_t:

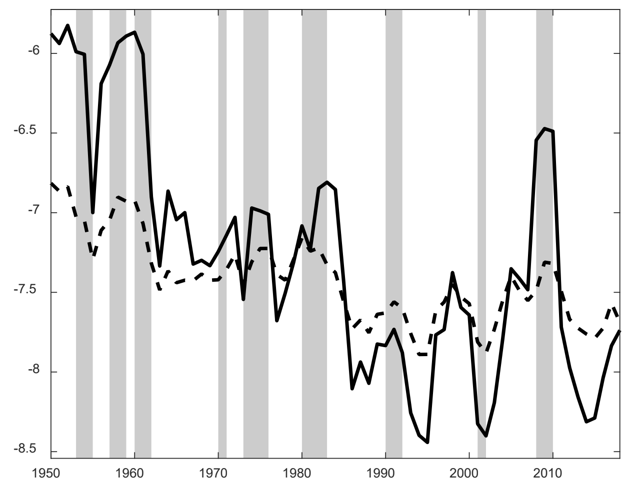
$$\log\left(RV_{t+1}\right) = \nu_0 + \nu'\Gamma_t + \varepsilon_{rv,t+1}, \tag{2}$$

and set the proxy for the ex-ante macro uncertainty to the exponentiated fitted value of the projection above:

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

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

Figure 1: **Realized and ex-ante log macro uncertainty**



The figure shows the time-series plot of the log realized variance $\log(RV_t)$ of industrial production (solid line) and the log of the ex-ante macro uncertainty $\log(v_t)$ (dashed line), averaged over the last three years $(t-2 \rightarrow t)$. The shaded areas represent NBER recessions.

The log transformation ensures that our ex-ante uncertainty measures is strictly positive.[7]

In the benchmark empirical implementation, we let y_t be industrial production growth, which is available at a monthly frequency,[8] and use that to construct its realized variance at the annual frequency. There are 12 observations of industrial production within one period, so that $N = 12$. We set the benchmark predictors Γ_t to include the log of realized variance, $\log(RV_t)$, the nominal risk free rate, r_f, the market return, r_m, 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 of uncertainty, both time-series are smoothed (averaged) 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

[7]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.

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

countercyclical, typically rising during the NBER recessions.

2.3 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 utilization and depreciation of existing capital;

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

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.

We start the analysis with plain correlations. Panel A of Table 1 shows contemporaneous correlations of each variable of interest Δy with macro uncertainty v_t. 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 regressions.[9] The Table shows that macroeconomic uncertainty has a negative correlation with the growth of δ, I/K, and u. This is generally consistent with the 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 is evidence is not driven by our specific methodology of constructing the ex-ante uncertainty v_t, in Panel A of Table 1 we also report

[9]While the stock of capital, K_t, is clearly non-stationary, several studies have pointed out that investment in fixed assets, 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.

Table 1: **Growth, uncertainty, and capital: Correlations**

y	Panel A: $\rho(\Delta y, v_t)$		Panel B: $\rho(\Delta y, g_t)$
	$v_t = E_t[RV_{t+1}]$	$v_t = RV_t$	
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 for each growth variable of interest Δy, specified in the left-most column, its contemporaneous correlation ρ with either v_t, macro uncertainty, or g_t, first-moment macro growth. The variables of interest are the stock of nonresidential capital, K, private nonresidential investment rate, I/K, nonresidential depreciation rate, δ, and capacity utilization, u. g_t is the first-moment macro growth, measured by annual consumption growth. v_t is measured either by the benchmark ex-ante volatility of industrial production ($E_t[RV_{t+1}]$), or by the realized variance of industrial production over the last 12 months, RV_t. Annual growth data on stock, investment rate, and depreciation for nonresidential private capital are from 1948-2018. Annual data on utilization rate are from 1967-2018.

the correlations between the growth rate in the aforementioned variables and the realized variance of industrial production over the last 12 months, 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).

Many economic models, including the one we develop in Section 3, 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. This macroeconomic fundamental feeds directly into the household's marginal utility. Consistent with existing models and empirical evidence, Panel B of Table 1 shows that the growth rates in I/K, δ, K, and u are procyclical, and have a positive correlation with g_t.[10]

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

[10] In Subsection 2.5, we consider the robustness of our main results to alternative methodologies of eliciting v_t from the data (e.g., GARCH-implied volatility), and to other proxies of g_t (e.g., log-TFP growth).

Table 2: **Uncertainty and capital accumulation**

Horizon K	β_v	t-stat	β_g	t-stat
y = Private nonresidendial 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 nonresidendial 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 nonresidendial 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: $\frac{1}{K}\Delta y_{t-1\to t+k-1} = const + \beta_v v_t + \beta_g g_t + error$. v_t is macro uncertainty, measured by the benchmark ex-ante volatility of industrial production. g_t is first-moment macro growth, measured by annual consumption growth. y is a variable of interest. Brackets report t-statistics. Standard errors are robust and Newey West adjusted. Annual growth data on stock, investment rate, and depreciation for nonresidential private capital are from 1948-2018. Data on capacity utilization rate are from 1967-2018. All variables are standardized, and annual.

moments of macroeconomic growth:

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

where $\Delta y_{t-1\to t+H-1} = \sum_{h=1}^{H} \Delta y_{t-1+h}$. For ease of interpretation, we standardize both the dependent and independent variables. 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 $H \in \{1, 2, 3\}$. The slope coefficients and their respective Newey-West t-statistics for the growth in investment rate, depreciation rate, utilization rate, and capital stock are shown in Table 2.

Consistent with the evidence presented in Table 1, the results in Table 2 show that the slope coefficient on g_t is positive at all horizons and for all capital-related growth variables. It is also always statistically significant in the contemporaneous regression, and significant in the predictive regressions for the growth in I/K, δ and K. The slope coefficient β_v is negative and significant (at the 10% level or higher) for both investment and depreciation growth rates. However, at all predictive horizons, the slope is more negative for depreciation than for investment growth rate. For example, for $H = 3$, β_v is -0.34 versus -0.20 when y is set to δ and I/K, respectively.

In-line with our findings that $\beta_{v,H|y=\delta} < \beta_{v,H|y=I/K} < 0$ for all H, we document that the slope coefficient β_v is positive and significant for capital growth. Specifically, at all the considered horizons, one standard deviation in v_t is associated with a 0.25 standard deviation increase in the future growth of capital, controlling for the other driving force g_t. This effect is economically sizable. It stands in contrast to the common notion that uncertainty should suppress the stock of capital due to its adverse effect on investment, but broadly consistent with the volatility overshoot effect documented in Bloom (2009). Table 1 also shows that uncertainty v_t negatively and significantly predicts the future utilization rate. The effect of uncertainty on utilization is as sizable (in absolute value) as that of first-moment fluctuations (i.e., g_t), and consistent with the relation between v and δ.

To further illustrate the impact of macro uncertainty on capital-related measures, Fig. 2 provides impulse responses of these growth measures to macro uncertainty shocks. The impulse response functions are computed from Smooth Local Projection (SLP) (Barnichon and Brownlees, 2019), which extends on the Local Projection methodology of Jordà (2005).

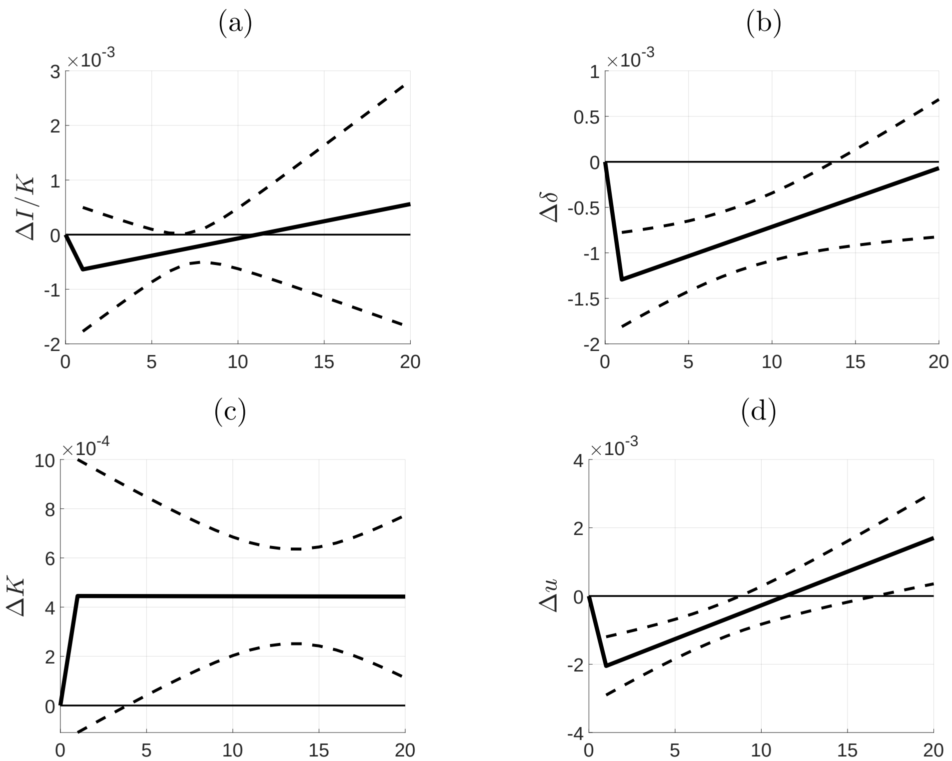
Specifically, let Y_t be the vector $[g_t, v_t, \Delta\delta_t, \Delta I/K_t, \Delta K_t]'$. Given this vector, the impulse response functions in panels (a) – (c) of Fig. 2 are derived from a full-sample SLP estimation of:

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

where y is the growth 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 growth using data from 1967-2018.

Figure 2: **Uncertainty shocks impulse responses: Benchmark**



The figure shows uncertainty impulse responses to the growth rate of (a) investment rate $\Delta I/K$, (b) depreciation rate $\Delta\delta$, (c) capital stock ΔK, and (d) utilization rate Δu. The investment and depreciation measures refer to private nonresidential capital. Let Y_t be the vector $[g_t, v_t, \Delta\delta_t, \Delta I/K_t, \Delta K_t]'$, where v_t is macro uncertainty measured by ex-ante industrial production volatility, and g_t is consumption growth. Given this vector, the impulse response functions in panels (a) − (c) are derived from smooth local projection (Barnichon and Brownlees (2019)) of: $y_{t+h} = \alpha_{(h)} + \beta_{(h)}v_t + \gamma(h)'\omega_t + u_{(h)t+h}$, where y is the growth variable of interest, and $\omega_t = [g_t, \Delta\delta_t, \Delta I/K_t, Y_{t-1}, Y_{t-2}, Y_{t-3}]$. The $\beta(h)$ is 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 base on a postwar sample from 1948-2018. In panel (d) we append the vector Y_t and the vector ω_t with Δu_t, and estimate the smooth local projection for utilization growth using data from the 1967-2018 sample.

Panels (a) of the figure demonstrate that the growth in investment rate falls due to a macro uncertainty shock. The negative effect of uncertainty on investment remains significant up to seven years ahead (followed by a qualitative overshoot, similar to Bloom (2009)). In contrast, panel (b) of Fig. 2 shows that the impact of uncertainty shock on depreciation growth 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 asymmetry in the impact of uncertainty on depreciation relative to investment echoes Table 2. Moreover, this asymmetry gives rise to a positive, significant, and persistent increase in future capital growth following an uncertainty shock (Panel (c)). Lastly, an uncertainty shock lowers capacity utilization's growth rate up to 8 years after.

2.4 Utilization and depreciation

Economic intuition suggests that utilization and depreciation comove positively with each other. An increase in utilization erodes equipment faster, persistently decreases its service life and thus raises the current and possibly future depreciation rate. We formally examine this link 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 3 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 impact 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 suggests that the utilization rate alone does not fully capture persistent fluctuations in the depreciation rate dynamics, a feature that we incorporate into our economic framework.

Table 3: **Depreciation and utilization**

Horizon K	β_δ	t-stat	β_u	t-stat
1			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: $\frac{1}{K}\Delta\delta_{t-1\to t+k-1} = const + \beta_\delta \Delta\delta_{t-1} + \beta_u u_t + error$. δ_t is private nonresidential depreciation rate. u_t is the capacity utilization rate. $\Delta\delta_{t-1}$ refers to the log growth rate between δ_{t-1} and δ_{t-2}. Brackets report t-statistics. Both the dependent variable and the independent variables are normalized. In the first row, the control $\Delta\delta_{t-1}$ is omitted, and the reported β_u is equal to the correlation between $\Delta\delta_t$ and u_t. Standard errors are robust and Newey West adjusted. Annual growth data on depreciation and utilization are from 1967-2018.

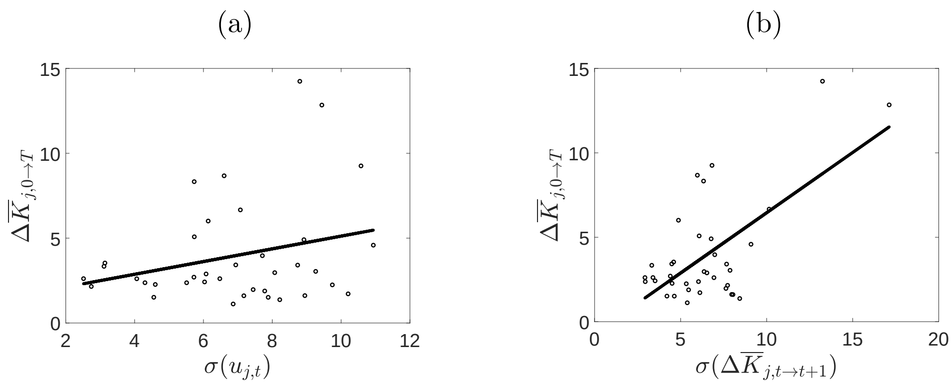
2.5 Robustness and extensions

In this section, we consider several extensions and robustness checks to support our main empirical results. We first examine the cross-sectional evidence between average uncertainty and capital growth across industries. Then, we extend the benchmark evidence to incorporate additional control variables, different subsample periods, alternative measures of first and second moment shocks, and alternative construction of the impulse responses through Cholesky decomposition.

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 collect industry-level data on capital stock and utilization rates. Specifically, we use the average growth in the book value of firms' total assets, 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 a mixture of durable producers, nondurable producers, mining and utilities. Our total cross-section encompasses 37 industries which have 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, $\Delta\overline{K}_{j,0\to T}$,

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



Panel A shows a scatter plot of all $\{(\Delta\overline{K}_{j,0\to T}, \sigma(u_j))\}_j$ pairs along with the best linear fit in the solid line. Panel B shows a scatter plot of all $\{(\Delta\overline{K}_{j,0\to T}, \sigma(\Delta\overline{K}_{j,t\to t+1}))\}_j$ pairs along with the best linear fit in the solid line. $\Delta\overline{K}_{j,0\to T}$ is industry j's capital growth over the entire sample period (averaged across all firms in the industry). $\sigma(\Delta\overline{K}_{j,t\to t+1})$ is industry j's standard deviation of average firm-level capital growth over each year. $\sigma(u_j)$ is industry j's standard deviation of utilization rate. The horizontal axes are in percentage points.

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.

Alternative measurements, controls and samples. In the first round of robustness checks we keep the benchmark measures v_t and g_t 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_t. 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 4 and 5) and Figures (Fig. OA.1.1 and Fig. OA.1.2). For all predictive horizons, the slope coefficient β_v is almost identical in magnitude and associated t-statistics to the benchmark results. In particular, uncertainty still predicts negatively (positively) depreciation (capital) growth rate, beyond the financial predictors, and the impulse response to depreciation

Table 4: **Uncertainty and depreciation: Robustness**

Horizon K	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 the realized variance of industrial-production, RV_t				
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]
Panel E: v_t is the ex-ante volatility of industrial-production when $\Gamma_t = [RV_t]$ 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 F: v_t is GARCH-based volatility of industrial production				
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 G: v_t is GARCH-based volatility of utilization-adjusted TFP				
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]

The table shows robustness results of the regression: $\frac{1}{K}\Delta\delta_{t-1\to t+k-1} = const + \beta_v v_t + \beta_g g_t + error$. δ_t is private nonresidential depreciation rate, v_t is macro uncertainty, and g_t is first-moment macro growth. Unless stated otherwise, v_t is measured via the ex-ante volatility of industrial production with the benchmark predictors Γ_t. Unless stated otherwise, g_t is consumption growth. In Panel A, the regression includes additional controls: the market return R_m, the 3 month T-bill yield r_f, and inflation π_t. In Panel B we focus on a model sample from 1968 (when utilization data is available)-2018. In all other panels data are from 1948-2018. In Panel C, g_t is TFP adjusted for utilization from Fernald (2014). In Panel D, v_t is the realized variance of industrial production over the last 12 months, RV_t. In Panel E, v_t is constructed similarly to the benchmark case, but when the predictor for volatility Γ_{t-1} includes only the lagged value RV_{t-1}. In Panel E, we estimate v_t using a GARCH(12,1) model over monthly industrial production, and average the volatility over the year. In panel G, we estimate v_t using GARCH(3,1) model over annual utilization-adjusted TFP data.

Table 5: **Uncertainty and capital stock: Robustness**

Horizon K	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 the realized variance of industrial-production, RV_t				
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 E: v_t is the ex-ante volatility of industrial-production when $\Gamma_t = [RV_t]$ 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 F: v_t is GARCH-based volatility of industrial production				
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 G: v_t is GARCH-based volatility of utilization-adjusted TFP				
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]

The table shows robustness results of the regression: $\frac{1}{K}\Delta K_{t-1\to t+k-1} = const + \beta_v v_t + \beta_g g_t + error$. K_t is the stock of private nonresidential capital, v_t is macro uncertainty, and g_t is first-moment macro growth. Unless stated otherwise, v_t is measured via the ex-ante volatility of industrial production with the benchmark predictors Γ_t. Unless stated otherwise, g_t is consumption growth. In Panel A, the regression includes additional controls: the market return R_m, the 3 month T-bill yield r_f, and inflation π_t. In Panel B we focus on a model sample from 1968 (when utilization data is available)-2018. In all other panels data are from 1948-2018. In Panel C, g_t is TFP adjusted for utilization from Fernald (2014). In Panel D, v_t is the realized variance of industrial production over the last 12 months, RV_t. In Panel E, v_t is constructed similarly to the benchmark case, but when the predictor for volatility Γ_{t-1} includes only the lagged value RV_{t-1}. In Panel E, we estimate v_t using a GARCH(12,1) model over monthly industrial production, and average the volatility over the year. In panel G, we estimate v_t using GARCH(3,1) model over annual utilization-adjusted TFP data.

(capital) growth remains negative (positive). Next, 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 of the Robustness Tables 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-statistic are quantitatively larger. The impulse response in Panel B of the Robustness Figures is still qualitatively negative (positive) for δ (K), but it loses significant at the 5% level, which occurs due to the shorter sample period.

In the next step of robustness checks, we alter the construction of v_t and g_t. The referenced panels henceforth refer to the Robustness Tables and Figures. In Panel C, g_t is TFP adjusted for utilization from Fernald (2014). In Panel D, v_t is the realized variance of industrial production over the last 12 months, RV_t.

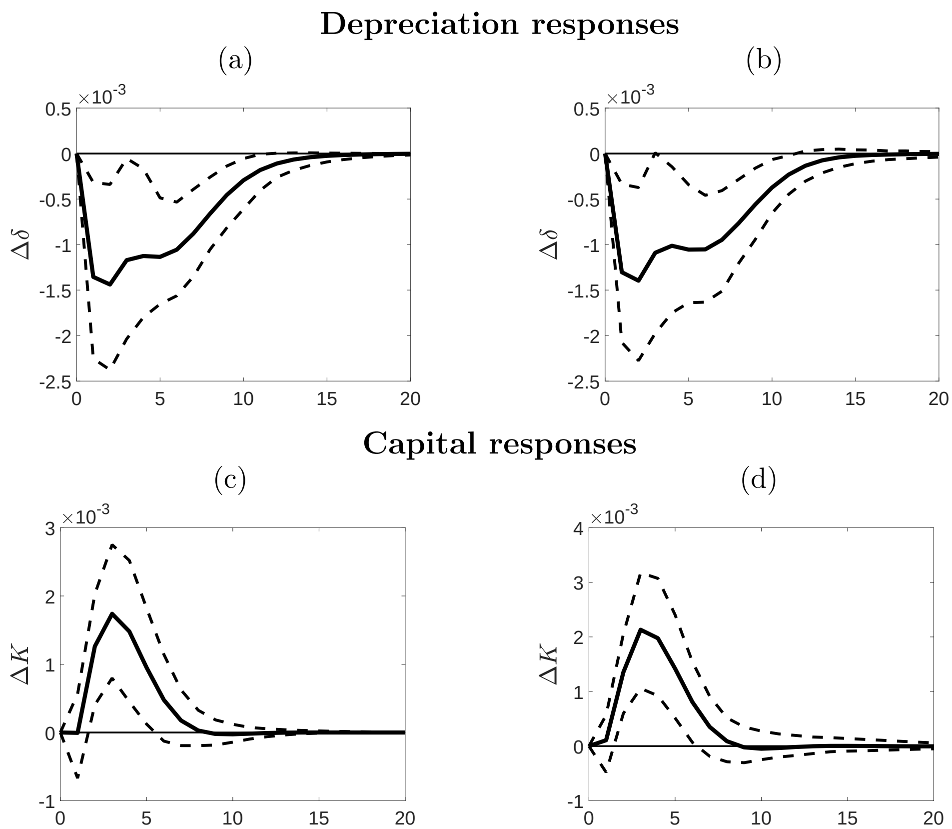
In Panel E, v_t is constructed similarly to the benchmark case, using projection (2), but when the predictor Γ_t includes only the lagged value RV_t. In Panel F, we estimate v_t using a GARCH model over monthly industrial production, and average the volatility over the year. In panel G, v_t is implied from a GARCH model estimated using annual utilization-adjusted TFP data.

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.

In Table OA.1.1 of the Online Appendix we consider further robustness checks for the predictive regressions: for example, we show that the results are robust to using the macro or financial uncertainty of Jurado, Ludvigson, and Ng (2015). We note that across all of the modifications, the results support the conclusion stated above.

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

Figure 4: **Uncertainty shocks impulse responses: Cholesky decomposition**



The figure shows impulse responses from a one standard deviation Cholesky uncertainty shock to depreciation growth $\Delta\delta$ (Panels (a) and (b)) and capital growth ΔK (Panels (c) and (d)). 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, and g_t is consumption growth. Horizontal axis represents years. The impulse response functions are obtain from a VAR(1) model with Cholesky decomposition. In Panels (a) and (c), the evidence is based on the benchmark vector Y_t, and the benchmark sample 1948–2018. In Panels (b) and (d), the evidence is based on augmenting the vector Y_t with the market return R_m, the 3 month T-bill yield r_f, and inflation π_t (in that order).

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 then estimate the following vector autoregressive (VAR(1)) 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,

$T(j, 3..N) = 0, \quad j \in \{1, 2\}$).[11] We derive impulse responses from one standard deviation uncertainty shocks to growth variables using Cholesky decomposition. Fig. 4 reports the results.

In panels (a) and (c) we show the impulse responses for depreciation and capital growth, respectively, estimated using the full sample period. Consistent with facts 1 and 2, 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 five times as large as in the benchmark evidence, shown in Panel (c) of Figure 2.

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

The robustness checks above support our benchmark evidence that high uncertainty is associated with a strong and pronounced decline in depreciation. The effect of uncertainty on capital growth is either 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 novel findings are challenging to reconcile within existing macroeconomic models, and develop and estimate a framework to explain the evidence.

3 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 has a persistent impact on future capital depreciation, which is a key novel channel in our model.

[11] In untabulated results we validate that we obtain almost identical results without imposing this restriction.

3.1 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. The exponent of A_t ensures balanced growth. u_t governs the intensity with which the firm utilizes its installed capital, K_t.[12]

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

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

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.[13]

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 shortens the service life of equipment. Consistent with the BEA computation of depreciation, this implies that existing equipment erodes faster, and therefore, a positive change in utilization is akin

[12]Featuring utilization as a variable that scales capital in Equation (6) is identical to extant modeling approaches (see, e.g., Basu, Fernald, and Kimball (2006), Jaimovich and Rebelo (2009), among others). 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)).

[13]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 3.3.

to a positive depreciation shock. This is also consistent with the empirical evidence presented in the first row of Table 3. The current depreciation shock is given by:[14]

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

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.[15] 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. This implies that the steady state value of $\varepsilon_\delta(u_t)$ is zero. When $\zeta \to \infty$, utilization is fixed at its steady-state level.

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

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

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 framework, 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. Moreover, such a specification of depreciation dynamics is well-motivated by empirical and economic considerations.

Empirically, the evidence presented in Table 3 indicates that the persistence in depreciation is larger than that of the utilization rate: future depreciation rates are significantly related to their own lagged values beyond the lagged utilization. A positive ρ_δ parameter is crucial to disentangle the persistence of the depreciation rate from that of the utilization rate. Indeed, we show in Section 3.6 that if $\rho_\delta = 0$,

[14] In our setup, a positive depreciation shock differs from capital disaster risk (see, e.g., Gourio, 2012, among others), in the sense that it is non-random: it endogenously depends on the utilization rate.

[15] 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.

then the autocorrelations of utilization and depreciation are nearly identical, which contradicts the empirical evidence.

Conceptually, several economic factors can explain why changes in the utilization rate induce a persistent effect on the depreciation rate. Any of these margins can potentially microfound the depreciation-utilization link posited in equation (10):

(i) **Capital reallocation**. According to the BEA, the depreciation rate of general equipment depends on the private sector it is used at.[16] 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 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.

(ii) **Composition of capital goods.** Depreciation also 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 changes in the utilization and the composition of capital, leading to a lead-lag dependence between utilization and depreciation.

    As an example, according to BEA measurements, fixed capital have a lower economic depreciation than inventory capital. Assume that a firm stops producing new goods, 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 drop in utilization at period t would decrease depreciation persistently.

[16] To illustrate this point, Figure OA.1.4 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).

(iii) **Vintage effects.** To capture economic depreciation, the BEA continuously updates equipment's service life to incorporate technological progress and better maintenance. Changes in service lives can induce a persistent effect on future depreciation rates, under the realistic assumption of complementary capital vintages.[17]

For parsimony, we focus on a standard specification of a single sector and a single type of capital, and thus leave the analysis of these other margins for a future work. Nonetheless, we argue that as an aggregate representation of the economy, Equation (10) captures in a reduced form richer dependence between utilization and depreciation originating from (i)–(iii) above.

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:

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

[17]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.

3.2 Household

The preferences of the representative household over the future consumption stream are characterized by the Kreps and Porteus (1978) recursive utility of Epstein and Zin (1991) and Weil (1989):

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

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. The first order condition of the household's maximization program imply that the stochastic discount factor (SDF) is given by:

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

wand the Euler condition for pricing any return R_j satisfies:

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

3.3 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 deterministic drift of productivity. Notably, volatility does not impact the drift of the productivity process, so we do not hardwire the first-order effects of volatility on the exogenous 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. 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.

3.4 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 holding $\{I_t, K_{t+1}, L_t, u_t, \delta_t, C_t, \Theta_t\}_{t=0}^{\infty}$ 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: $\Theta_t = 1, \quad \forall t$.

3.5 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 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. In particular, the utilization choice is directly affected by the precautionary saving motive, via discount rates, similar to the investment choice.

3.6 Estimation

Table 6 shows the benchmark model parameters. 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), and Croce (2014), among others.

Table 6: **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. All non-bold parameters are estimated via SMM. Bold parameters are calibrated.

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 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 7 shows the moment conditions we use to estimate the model. We group the moments into two categories.[18] (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 model parameters.

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 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 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 0.45 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 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 0.18%, 0.26% and 0.50%, respectively, all close to the data.

[18] The table shows all macro-related moments used in the estimation. See Table 8 for the risk-free rate moment.

Table 7: **Model-implied macroeconomic moments**

	Model		Data
Panel A: Unconditional annual moments.			
Consumption growth.			
Mean (%)	1.82	[0.60, 3.69]	1.81
Std. Dev. (%)	2.10	[1.20, 4.58]	1.22
AC(1)	0.45	[0.14, 0.72]	0.47
Output growth.			
Mean (%)	1.85	[0.54, 3.82]	1.78
Std. Dev. (%)	2.42	[1.36, 5.60]	1.92
AC(1)	0.47	[0.17, 0.68]	0.25
Investment growth.			
Mean (%)	1.89	[0.34, 3.94]	1.25
Std. Dev. (%)	3.40	[1.74, 8.00]	5.83
AC(1)	0.39	[0.11, 0.63]	0.27
Depreciation rate.			
Mean (%)	8.50	[7.53, 9.80]	8.34
Std. Dev. (%)	0.33	[0.13, 0.73]	0.51
AC(1)	0.98	[0.93, 0.99]	0.96
Utilization rate.			
Std. Dev. (%)	4.77	[2.92, 8.45]	4.17
AC(1)	0.76	[0.39, 0.92]	0.62
Panel B: Realized volatility moments.			
Consumption growth.			
Std. Dev. (%)	0.18	[0.08, 0.51]	0.14
AC(1)	0.97	[0.90, 0.99]	0.97
Output growth.			
Std. Dev. (%)	0.26	[0.10, 0.77]	0.30
AC(1)	0.98	[0.94, 0.99]	0.98
Investment growth.			
Std. Dev. (%)	0.50	[0.17, 1.36]	0.63
AC(1)	0.98	[0.91, 0.99]	0.96

The table shows model-implied macroeconomic moments along with their empirical counterparts. Panel A shows unconditional moments for annual growth and rate variables. Panel B shows realized volatility moments computed at the quarterly frequency. We compute the realized volatility of each variable using a 5-year (20 quarters) rolling standard deviation. In both panels, the model-implied moments are based on 200 simulation of short sample paths, where each path is 612 months. In Panel A (B) each model-implied path is aggregated to form annual (quarterly) observations spanning 51 years (204 quarters). For each moment of interest, the table shows the median value, along with the corresponding 5th and 95th percentiles in brackets. The empirical moments are based on a modern sample from 1968 to 2018, for which utilization growth data is available.

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 8.5%, 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, and the projection evidence in Table 3. Given this estimate, the autocorrelation of the annual depreciation rate is 0.98 in the model versus 0.96 in the data. At the same time, the autocorrelation of the utilization rate is 0.76 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.

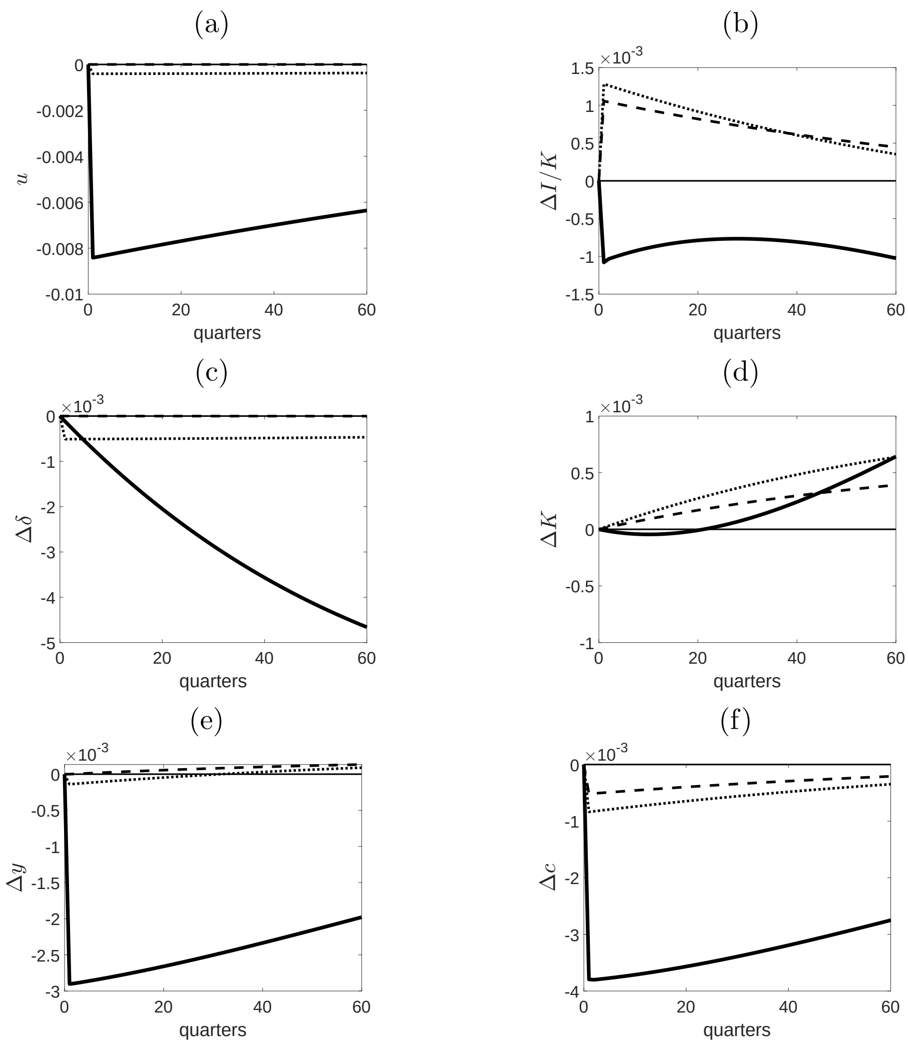
The parameter ζ governs the volatility of utilization rate, which amounts to 4.2% in the data, and consequently, also impacts the volatility of the depreciation rate, which is 0.5%. Both volatilities fall within the model's confidence interval.

Lastly, the estimate of β is 0.998. It is identified using the mean, standard deviation, and autocorrelation of the risk-free rate. The risk-free rate is 0.87% in the model compared to 1.04% in the data.

4 Uncertainty shocks and 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, (b) positive association between uncertainty and future capital growth, in spite of a drop in investment, and (c) positive and persistent effect of utilization on capital depreciation rate. 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

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



The figure shows model-implied uncertainty impulse responses to (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. 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 quarters. The vertical axis represents deviations from the steady-state value.

fails to produce an uncertainty-driven recession. We then show in Subsection 4.2 that flexible utilization coupled with persistence in depreciation go a long way to account for these features of the data.

4.1 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.

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 investing and building up a stock of capital that can be used for production and consumption in the future.[19]

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. 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 (d) 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 falls and the depreciation rate 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

[19] 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.

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, Ma, and Ng (2019), 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.

Since the 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.

4.2 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), which describes the optimal choice of capacity utilization, explicitly links utilization to the depreciation rate of capital: 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 stock of capital, 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 4.1, a positive uncertainty shock ε_w causes the risk-free rate to persistently decline. Because discount rates fall, 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 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 4.1 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.[20] 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 4.1. 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

[20] Specifically, the utilization growth rate immediately drops by 0.6% after an uncertainty shock, whereas R_f (not shown in Figure 5) drops by 0.01%.

on cumulative capital growth in the model. Cumulative capital growth overshoots after about 20 quarters, whereas the initial effect of uncertainty on capital is close to zero[21] 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 4.2.2).

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 second effect of a decrease in depreciation dominates the decrease in investment, and boosts medium- to long- term capital growth.[22]

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

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

[22]While not reported, the divergence between investment and capital growth occurs only with respect to uncertainty shocks. A negative first-moment shock drops both investment and depreciation, however, the former always dominates. The comovement of investment and capital growth following a level shock is in-line with the data.

and capital growth following uncertainty shocks.[23]

Output and consumption. In contrast to a model with fixed utilization, contemporaneous output can decrease with uncertainty, because of the immediate drop in installed capital 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 response evidence shows 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 4.1), the consumption drop is smaller in that case compared to the flexible utilization model.

4.2.1 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 ($\rho_\delta = 0$).

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

[23]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 depreciation. 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.1.3 that an uncertainty shock leads to a drop in both investment and future capital growth in their model, in contrast to our evidence.

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.

Intuitively, as shown in Section 3.5, when $\rho_\delta = 0$ the utilization's choice is static. The benefit of reducing utilization is that it slows down the depreciation rate per unit of capital 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 becomes much smaller, and this affects other variables of interest.

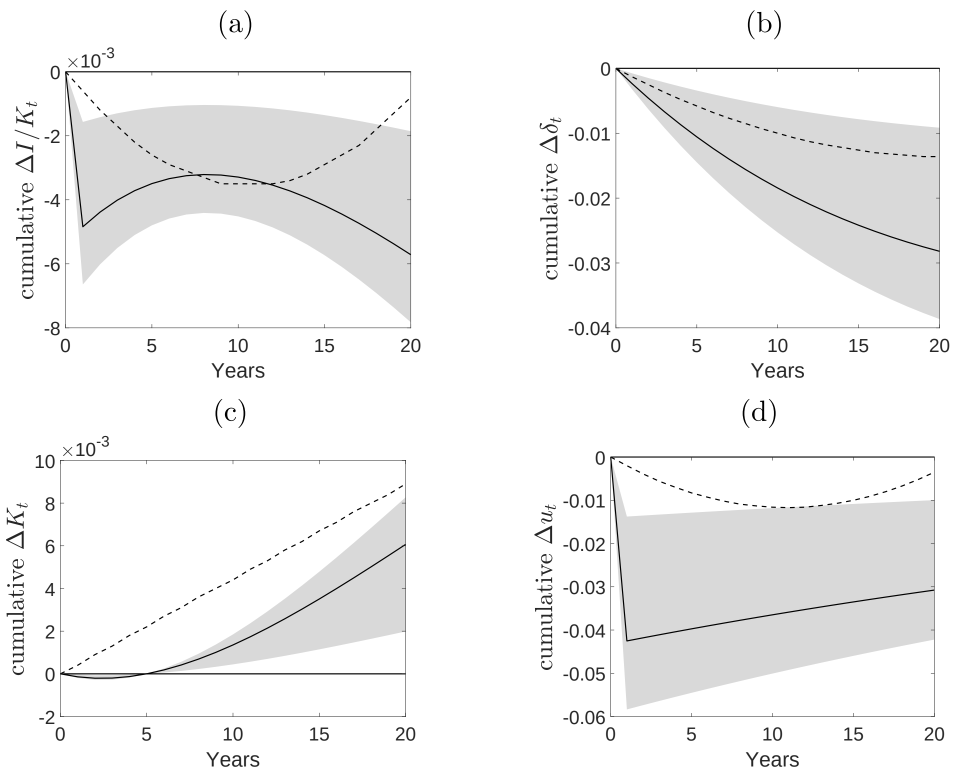
Specifically, the drop in the magnitude of utilization's response qualitatively affects the investment dynamics. Panel (b) shows that if $\rho_\delta = 0$, the investment rate growth increases, despite the decrease in utilization. Recall that investment is determined by the trade-off between a drop in 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 empirical evidence.

4.2.2 Quantitative comparison

The impulse responses in the model depicted in Figure 5 are quarterly 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 four-quarter 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 that the frequency of the observations is annual.

Figure 6 shows the model-implied cumulative impulse responses of the log-growth rates in investment, depreciation, capital, and utilization to the empirically-equivalent

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



Model-implied empirically-equivalent impulse responses (black) and empirical impulse responses (dashed).

uncertainty shock. Their confidence intervals are shown in the shaded regions. The data are shown in dashed lines, and obtained by accumulating the impulse responses from 0 up to horizon $h \in \{0..20\}$ in Figure 2.

We emphasize that 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 empirical counterpart at longer horizons.

4.2.3 Comparison to the New-Keynesian approach

Basu and Bundick (2017) and Fernández-Villaverde et al. (2015) show that a new-Keynesian model that features time-varying markups can induce a comovement between consumption and investment in response to uncertainty shocks. In online appendix OA.2 we extend our baseline model of Section 3 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 shocks. 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.

5 Uncertainty shocks and asset prices

5.1 Uncertainty and the equity premium

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 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. We set σ_d to target the volatility of excess returns

Table 8: **Model-implied asset prices**

Panel A: Asset pricing moments

	Model		Data
Market Excess Return.			
Mean (%)	7.08	[1.77, 14.40]	4.58
Std. Dev. (%)	17.34	[13.64, 23.28]	17.09
AC(1)	-0.01	[-0.34, 0.34]	-0.05
Risk-free rate.			
Mean (%)	0.87	[0.28, 1.97]	1.04
Std. Dev. (%)	1.06	[0.56, 2.14]	1.71
AC(1)	0.56	[0.21, 0.78]	0.79

Panel B: Equity premium decomposition

	$E[R^e_m]$ (%)	Contribution First-Moment	Contribution Second-Moment	$\sigma(\Delta c)$ (%)
(1) Data	4.58	-	-	1.22
(2) Benchmark	7.08	73.24%	26.75%	2.09
(3) Fixed Utilization	2.19	196.82%	-96.82%	1.90
(4) Non extra persistence in depreciation	2.13	277.03%	-177.03%	1.96

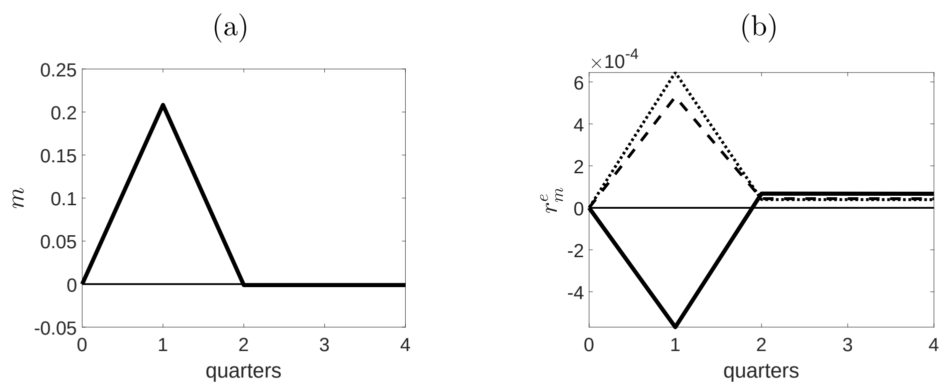
Panel A of the table shows model-implied asset-pricing moments along with their empirical counterparts. The model-implied moments are based on 400 simulation of short sample paths, where each path is 612 months. Each model-implied path is aggregated to form annual observations spanning 51 years. For each moment of interest, the table shows the median (annual) value, along with the corresponding 5th and 95th percentiles in brackets. The empirical moments are based on a modern sample (1968-2018) of annual observations, for which utilization growth data is available. For each moment we report its empirical value along with the 90% confidence interval in brackets.
Panel B of the table shows the empirical and model-implied moments for the equity premium $E[R^e_m]$, as well as the decomposition of the equity premium to first- and second- moment productivity shocks. For ease of comparison across calibrations, we also report consumption growth's volatility $\sigma(\Delta c)$. The results are shown for the benchmark parameters, we well as for a calibration that features fixed utilization ($\zeta \to \infty$), and a calibration with flexible utilization but no extra persistence in depreciation dynamics ($\rho_\delta = 0$). The model-implied moments are based on 400 simulations of short sample paths, where each path is 612 months. Each model-implied path is aggregated to form annual observations spanning 51 years. For each moment of interest, the table shows the median (annual) value. The empirical moments are based on a modern sample (1968-2018) of annual observations, for which utilization growth data is available.

in the data.

Unconditional pricing moments. Panel (a) of Table 8 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 7.08%, 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.

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 $\rho_\delta = 0$. 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 $M_{t-t,t}$.

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



The figure shows model-implied uncertainty impulse responses to (a) the marginal utility m, (b) excess returns, r^e_d. The solid line shows the results using the benchmark model parameters. The dotted line shows the results with no extra persistence in depreciation, $\rho_\delta = 0$. The dashed line shows the results when $\zeta \to \infty$ (fixed utilization). All growth impulse responses are cumulative.

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 4.1, 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.[24] 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 8, with fixed utilization the contribution of uncertainty shock to the equity premium is -96.8%. The equity premium under fixed utilization is 2.2%, which is about one-and-a-half lower than the benchmark model-implied equity premium, despite the fact that the two specifications feature nearly identical consumption volatility; see Table 8.

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 that in the benchmark specification, as tabulated in Row (4) of Panel (B) in Table 8.

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 8, 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.

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

5.2 Uncertainty risk exposures: Cross-sectional evidence

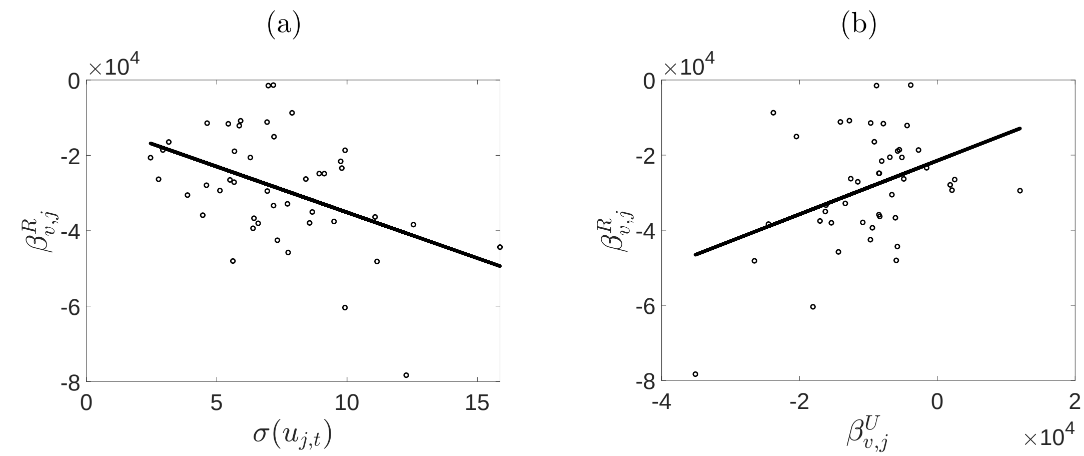
Our model provides additional implications for the connection between utilization, uncertainty, and asset prices which we can test in the cross-section of returns in the data. First, the model suggests that the uncertainty exposures of a firm return and utilization rate are related: the more sensitive 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. To see this, note that Section 5.1 shows that when utilization is fixed ($\zeta \to \infty$), firms' exposure to uncertainty shocks is positive, and the contribution of these shocks to the equity premium is negative. However, when utilization is sufficiently time-varying, as in the benchmark parametrization ($\zeta = 0.93$), firms' exposure to uncertainty shocks turns negative, and the contribution of these shocks to the equity premium is 26%. This result is monotonic in ζ. We find that the relative contribution of uncertainty shocks to the model-implied equity premium is 34.9%, 9.22%, and -38.76%, when ζ equals to 0.5, 2, and 10, respectively.[25]

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 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

[25] Similarly, the annualized uncertainty risk exposure of the firm is -0.048, -0.029, -0.006, and 0.020 when ζ equals to 0.5, 0.93, 2, and 10, respectively.

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



The figure shows a scatter plot of all $\{(\beta^R_{v,j}, \sigma(u_j))\}_j$ pairs (Panel A) and all $\{(\beta^R_{v,j}, \beta^U_{v,j})\}_j$ pairs (Panel B) along with the best linear fit in the solid line, estimated by Equation (29) (Equation (30)). $\beta^R_{v,j}$ is industry j's uncertainty risk exposure, estimated from projection (27). $\beta^U_{v,j}$ is industry j utilization's sensitivity to uncertainty shocks, estimated from projection (28). $\sigma(u_j)$ is industry j's standard deviation of utilization rate.

the first-difference of macro uncertainty ($\Delta v_t = v_t - v_{t-1}$) and macro growth ($g_t$):

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

The measures v_t and g_t are identical to those described in Section 2.2. 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)). $\beta^R_{v,j}$ is the exposure of industry j to macro uncertainty.

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. We also estimate the volatility (standard deviation) of the capacity utilization rate for each industry j, $\sigma(u_j)$.

Next, we run two cross-sectional regressions, as follows:

$$\beta^R_{v,j} = c_0 + c_u \cdot \sigma(u_j) + error, \tag{29}$$

$$\beta^R_{v,j} = d_0 + d_u \cdot \beta^U_{v,j} + error, \tag{30}$$

In regression (29), we project uncertainty risk exposure on utilization's volatility of each industry. In regression (30), we project uncertainty risk exposure of each industry on its utilization's sensitivity to uncertainty.

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 best linear fit, captured by Equation (29) (Equation (30)). First, for almost all industries, the uncertainty risk exposure is negative, in line with existing studies. Almost all utilization elasticities to macro uncertainty are negative. Second, we find that $c_u < 0$. The cross-sectional correlation between $\{\beta^R_{v,j}\}_j$ and $\{\sigma(u_j)\}_j$ is -0.45 with $p - val < 1\%$. Third, we obtain that $d_u > 0$. The correlation between $\{\beta^R_{v,j}\}_j$ and $\{\beta^U_{v,j}\}_j$ is 0.39 with $p - val = .02$. This confirms the model's predictions: industries with a more volatile utilization rate and/or with more negative elasticity of utilization to uncertainty have more negative exposure to macro uncertainty.

6 Conclusion

We provide novel empirical evidence for the propagation of uncertainty shocks in 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. 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. Firms optimally choose to decrease the utilization of the existing capital as a substitute for investing into new capital in response to heightened risk and uncertainty. Reducing utilization lowers capital depreciation rate, and preserves capital for future use as a buffer against bad productivity shocks, without the need to acquire equipment and pay adjustment costs associated with its installation. This substitution between utilization and investment goes a long way to reconcile the empirical evidence. A decrease in future utilization is isomorphic to a drop in the firm's productivity, which lowers the expected marginal product of capital, and suppresses current investment. Persistence in depreciation magnifies the impact of uncertainty on depreciation, so that the savings from a reduction in depreciation more than compensate for a decline in investment. Consequently, future capital growth rises, as in the data.

We further show that uncertainty shocks are associated with a high marginal utility of the representative agent and a decrease in equity valuations. Taken together, this implies that uncertainty shocks contribute positively to the level and variation in the equity premium. The model provides testable 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 the volatility-utilization-depreciation channel plays to explain the macroeconomic and asset-price data. Our mechanism is simple to incorporate into any production model, and it gives rise to a rich and empirically relevant interplay between risk and capital accumulation, as well as realistic qualitative implications for asset-pricing studies.

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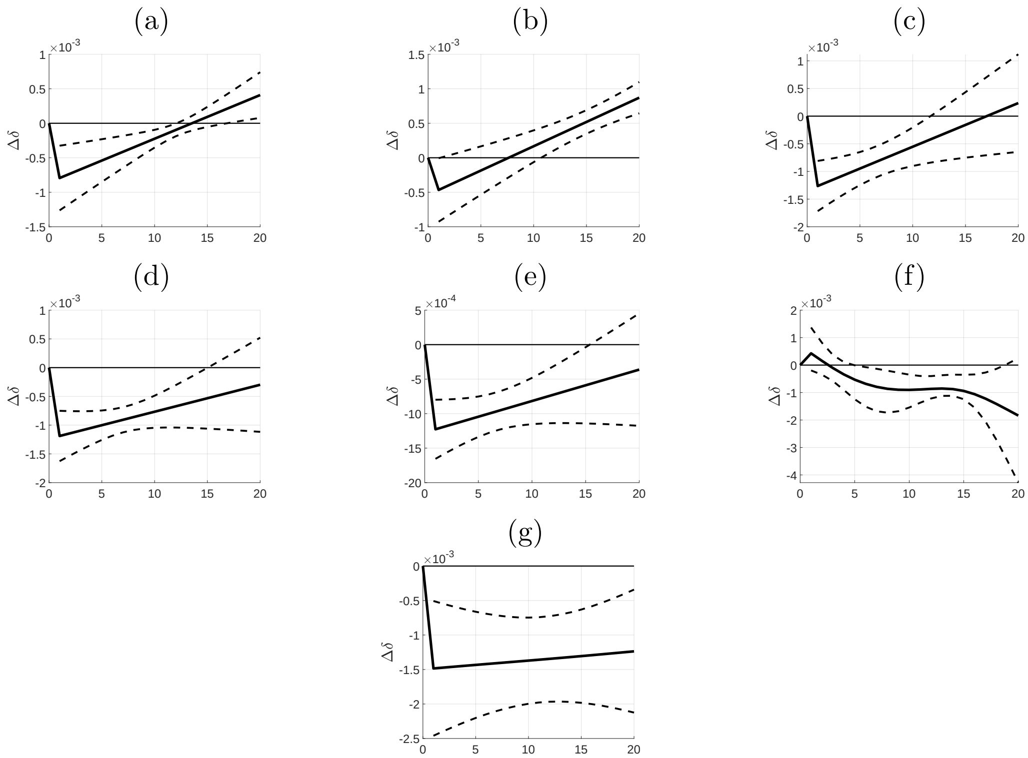
Online appendix

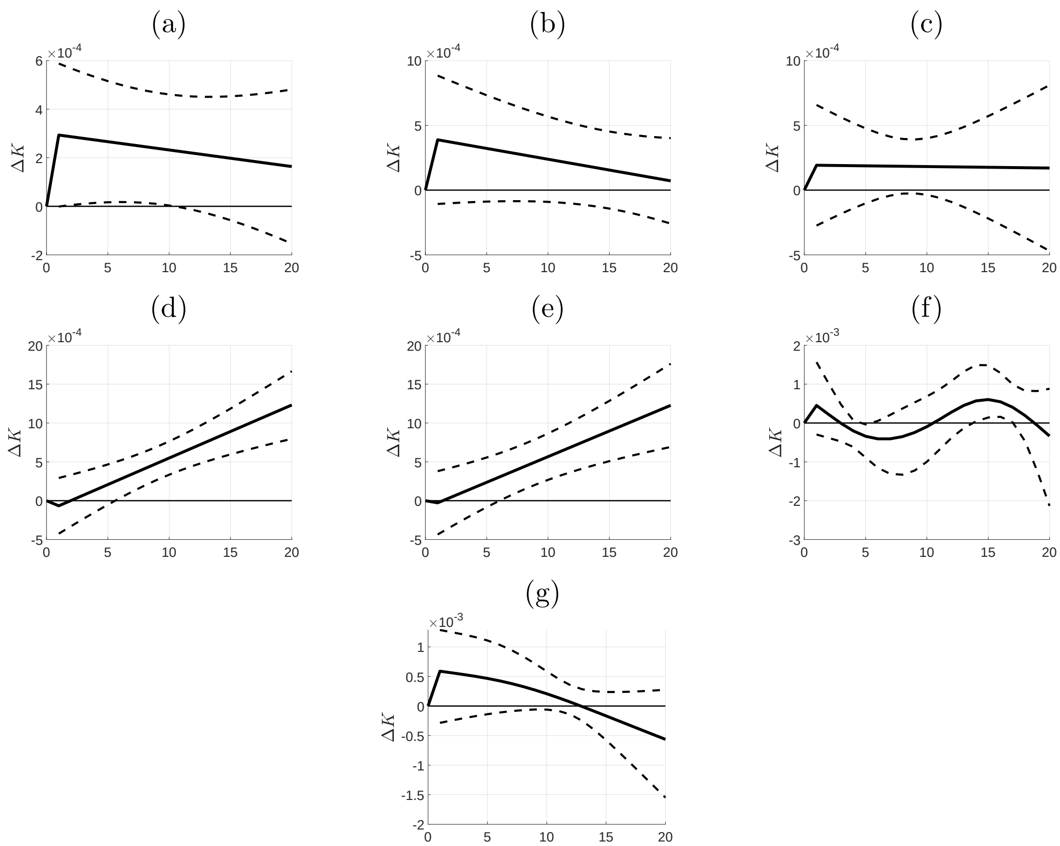
OA.1 Supplemental tables and figures

Figure OA.1.1: **Uncertainty shock IR to depreciation: robustness**



The figure shows robustness checks for uncertainty's impulse responses to the growth rate of depreciation $y = \Delta\delta$. The methodology for constructing the impulse response is a smooth local projection (SLP) (Barnichon and Brownlees (2019)), identical to the description in Figure 2, unless stated otherwise. The dashed lines represent the 90% confidence interval. In Panel A, the vector Y_t and the vector ω_t are augmented with additional controls: the market return R_m, the 3 month T-bill yield r_f, and inflation π_t. In Panel B we focus on a model sample from 1968 (when utilization data is available)-2018. In all other panels data are from 1948-2018. In Panel C, g_t is TFP adjusted for utilization from Fernald (2014). In Panel D, v_t is the realized variance of industrial production over the last 12 months, RV_t. In Panel E, v_t is constructed similarly to the benchmark case, but when the predictor for volatility Γ_{t-1} includes only the lagged value RV_{t-1}. In Panel E, we estimate v_t using a GARCH(12,1) model over monthly industrial production, and average the volatility over the year. In panel G, we estimate v_t using GARCH(3,1) model over annual utilization-adjusted TFP data.

Figure OA.1.2: **Uncertainty shock IR to capital: robustness**



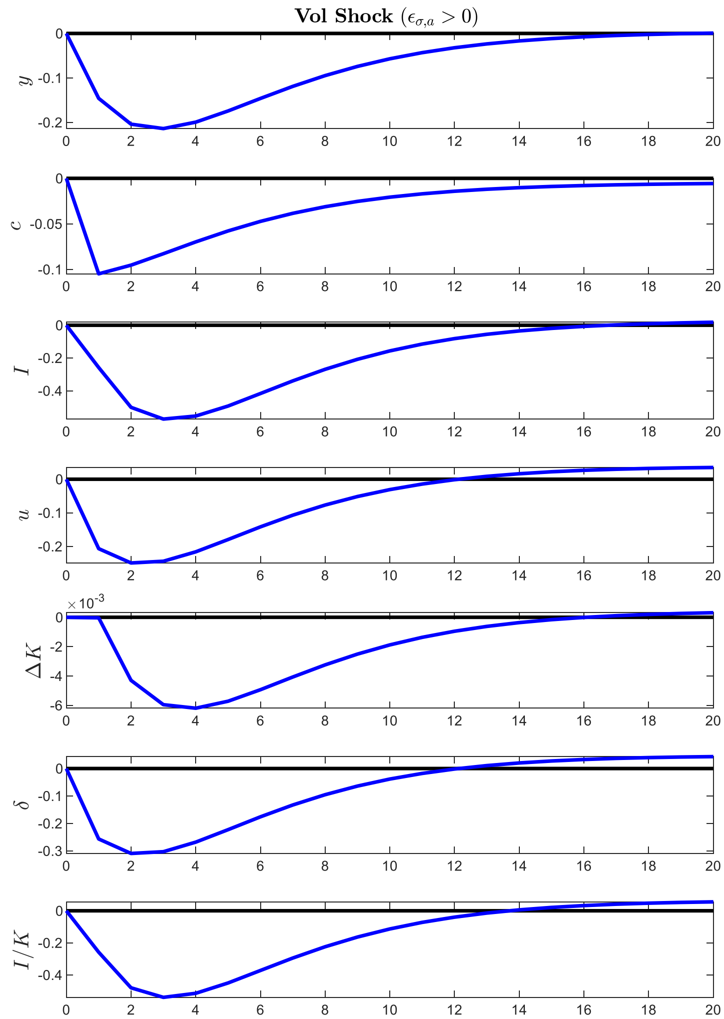
The figure shows robustness checks for uncertainty's impulse responses to the growth rate of private nonresidential capital $y = \Delta K$. The methodology for constructing the impulse response is smooth local projection (SLP) (Barnichon and Brownlees (2019)), identical to the description in Figure 2, unless stated otherwise. The dashed lines represent the 90% confidence interval. In Panel A, the vector Y_t and the vector ω_t are augmented with additional controls: the market return R_m, the 3 month T-bill yield r_f, and inflation π_t. In Panel B we focus on a model sample from 1968 (when utilization data is available)-2018. In all other panels data are from 1948-2018. In Panel C, g_t is TFP adjusted for utilization from Fernald (2014). In Panel D, v_t is the realized variance of industrial production over the last 12 months, RV_t. In Panel E, v_t is constructed similarly to the benchmark case, but when the predictor for volatility Γ_{t-1} includes only the lagged value RV_{t-1}. In Panel E, we estimate v_t using a GARCH(12,1) model over monthly industrial production, and average the volatility over the year. In panel G, we estimate v_t using GARCH(3,1) model over annual utilization-adjusted TFP data.

Table OA.1.1: **Uncertainty, capital, and depreciation: Other robustness**

Horizon K	β_v	t-stat	β_g	t-stat
Panel A: Results for nonresidential equipment				
$y = \delta_t$				
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]
$y = K_t$				
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: Growth of future y with respect to time t				
$y = \delta_t$				
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]
$y = K_t$				
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_t is macro uncertainty of Ludvigson et al. (2019)				
$y = \delta_t$				
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]
$y = K_t$				
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 D: v_t is financial uncertainty of Ludvigson et al. (2019)				
$y = \delta_t$				
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]
$y = K_t$				
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 E: v_t is policy uncertainty of Baker et al. (2016)				
$y = \delta_t$				
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 robustness results of the regression: $\frac{1}{K}\Delta y_{t-1\to t+k-1} = const + \beta_v v_t + \beta_g g_t + error$, where y is either δ_t is private nonresidential depreciation rate, or K_t the stock of nonresidential capital. v_t is macro uncertainty, and g_t is first-moment macro growth. Unless stated otherwise, v_t is measured via the ex-ante volatility of industrial production with the benchmark predictors Γ_t. Unless stated otherwise, g_t is consumption growth. In Panel A, the depreciation and capital stock are of private non residential equipment only. In Panel B, the dependent variable is $\frac{1}{K}\Delta y_{t\to t+k}$. In Panel C (D), v_t is macro (financial) uncertainty of Ludvigson et al. (2019) from 1967 onward.

Figure OA.1.3: **Basu and Bundick (2017): Deprecation, and capital growth**



The figure shows our replication of Basu and Bundick (2017) impulse responses under the benchmark calibration. The vertical axis represent percent deviation from the steady state value. The first three IRFs for y is output, c is consumption, and I is investment, 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.

Figure OA.1.4: **General equipment depreciation rate: 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 depreciation rate of general equipment as of 2013, contingent on the sector of usage.

OA.2 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 3. Unlike the perfect competition model, we now assume that 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 $y_t(m)$. Its output 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:

$$Y_t = \left[\int_0^1 y_t(m)^{\frac{\theta-1}{\theta}} dm \right]^{\frac{\theta}{\theta-1}}, \tag{31}$$

when $\theta \to \infty$, the intermediate good producers face perfect competition. For any finite θ, the intermediate good producers are not perfect substitutes, and they possess some amount of monopolistic power.

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

$$\max_{\{y_t(m)\}} \quad P_t Y_t - \int_0^1 p_t(m) y_t(m) dm$$
$$\text{s.t equation (31).}$$

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

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 3.1. It owns its capital stock, $K_t(m)$, which depreciates at rate $\delta_t(m)$, and it hires labor from the household. Now, however, it has an additional degree of freedom: the ability to optimally select its nominal output price. Specifically, the real period dividend of an intermediate good producer of variety m, $d_t(m)/P_t$, is given by:

$$d_t(m)/P_t = \left[\frac{p_t(m)}{P_t}\right]^{1-\theta} Y_t - I_t - W_t/P_t \cdot L_t(m) - \phi_P/2\left(\frac{p_t(m)}{\Pi p_{t-1}(m)} - 1\right)^2 Y_t, \quad (32)$$

where, as before, W_t denotes the real wage per unit of labor, and 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 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:

$$V_t(m) = \max_{\{L_s(m)\, p_s(m),\, K_{s+1}(m)\, u_s(m)\}} \quad E_t \sum_{s=t}^{\infty} M_{t,s}(d_s(m)/P_s) \quad (33)$$

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. The following Euler condition holds in equilibrium: $1/R_t = E_t\left[\frac{M_{t+1}}{\Pi_{t+1}}\right]$.

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 AR(1) dynamics as described in Eq (18).

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

$$\int_0^1 L_t(m)dm = 1,$$

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

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 (33); (ii) all markets clear; (iii) we are interested in a symmetric equilibrium in which $K_t(m) = K_t$, $u_t(m) = u_t$, $L_t(m) = L_t$, and $p_t(m) = p_t$, for all $m \in [0, 1]$.

Calibration. All model parameters are identical to those specified in Section 3.6, 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 6).

Impulse responses. Figures OA.2.5 and OA.2.6 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 proposed 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

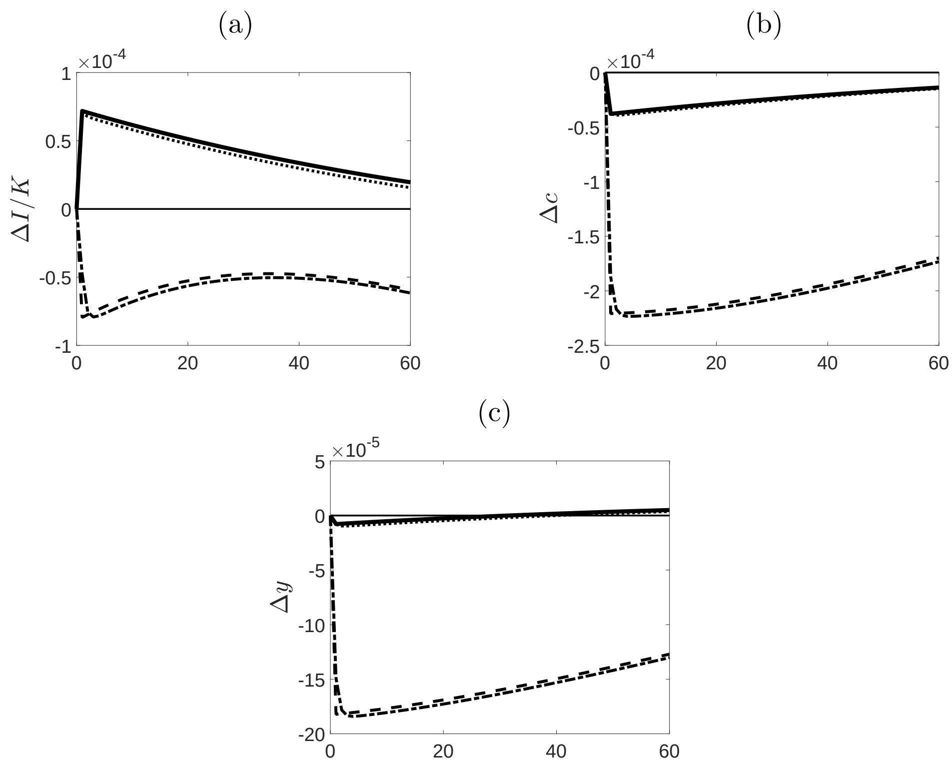
and output following an uncertainty shock. All real quantities decrease in the presence of fixed but positive markups;

(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 is 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.

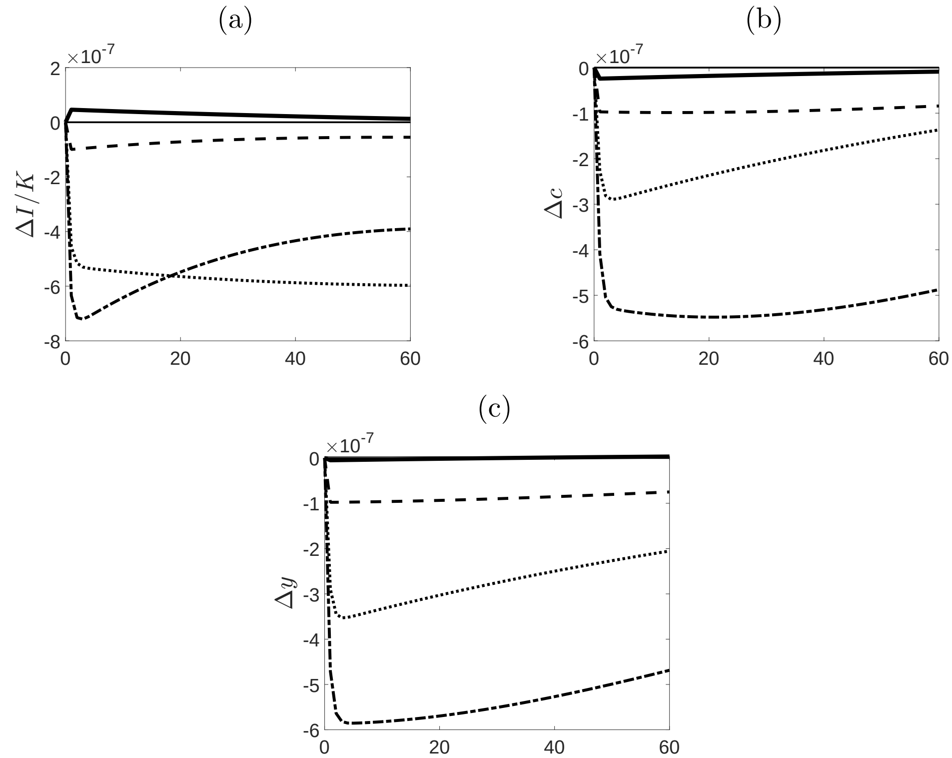
(4) Under transitory productivity shocks, the time-varying markup channel alone (i.e., $\rho_\delta = 0$ but $\phi_P = 100$) is sufficiently strong as to drop consumption, investment and output, following an uncertainty shock. This is consistent with the results of Basu and Bundick (2017), that study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

Figure OA.2.5: **Model-implied impulse responses to uncertainty shocks: 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. The solid line shows the results for a calibration with no persistent depreciation and no price stickiness ($\rho_\delta = 0$, $\phi_P = 0$). The dashed line shows the results for a calibration with persistent depreciation but no price stickiness ($\rho_\delta = 0.99$, $\phi_P = 0$). The dotted line shows the results for a calibration with no persistent depreciation but with price stickiness ($\rho_\delta = 0$, $\phi_P = 100$). The dotted-dashed line shows the results for a calibration with persistent depreciation and price stickiness ($\rho_\delta = 0.99$, $\phi_P = 100$). 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.

Figure OA.2.6: **Model-implied impulse responses to uncertainty shocks: 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. The solid line shows the results for a calibration with no persistent depreciation and no price stickiness ($\rho_\delta = 0$, $\phi_P = 0$). The dashed line shows the results for a calibration with persistent depreciation but no price stickiness ($\rho_\delta = 0.99$, $\phi_P = 0$). The dotted line shows the results for a calibration with no persistent depreciation but with price stickiness ($\rho_\delta = 0$, $\phi_P = 100$). The dotted-dashed line shows the results for a calibration with persistent depreciation and price stickiness ($\rho_\delta = 0.99$, $\phi_P = 100$). 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.