When in Doubt, Tax More Progressively? Uncertainty and Progressive Income Taxation*

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Abstract

We examine the optimal income tax problem when policymakers face parameter uncertainty regarding household preferences and wage process. We derive conditions that qualitatively characterize how parameter uncertainty influences optimal tax policy. To quantify this effect, we develop and estimate an incomplete-market life-cycle model of heterogeneous households using a Bayesian approach with U.S. data. Our findings reveal that parameter uncertainty leads to a more progressive optimal income tax policy, corresponding to a 5.5 percentage-point increase in the marginal tax rate gap between high- and low-income households. This effect is driven primarily by uncertainty about wage process. We also find sizable welfare cost of parameter uncertainty through the income tax channel alone.

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1 Introduction

How should the government tax people's income? This fundamental question has long been a central focus of economic research. Through theoretical and quantitative approaches, researchers have identified key factors that influence tax design, such as the elasticity of labor supply and the idiosyncratic risks individuals bear. However, policymakers face a significant challenge: they often lack precise knowledge about these factors. Because these factors are not directly observable and their values are typically estimated from micro survey data, parameter uncertainty becomes an inherent aspect of the policy decision-making process. Despite its importance, the impact of parameter uncertainty on optimal income tax policy remains underexplored—a gap this paper aims to address.

Our research contributes to the extensive literature in the macroeconomic aspects of public finance that employs parameterized structural models to investigate optimal tax questions within the Ramsey tradition. Influential studies in this field typically rely on fixed parameter values, often point estimates, for policy analyses.[1] Departing from this standard approach, this paper introduces a framework that explicitly incorporates policymakers' concerns about parameter uncertainty, thereby examining how uncertainty regarding household preferences and wage dynamics affects the optimal design of income tax policy.

Specifically, we make two main contributions to the literature: one theoretical and one quantitative. First, we provide general theoretical insights into how parameter uncertainty, as captured by the policymakers' posterior distribution, influences optimal policy. We identify conditions that determine the direction of policy adjustment once parameter uncertainty is considered, and emphasize the critical role of correlations among uncertain parameters.

Second, we demonstrate the quantitative significance of parameter uncertainty in shaping optimal income tax policy. Using a dynamic life-cycle model of two-earner households, with parameter uncertainty quantified through a limited-information Bayesian approach, we show that neglecting parameter uncertainty can lead to con-

[1] See, for example, Bénabou (2002), Conesa and Krueger (2006), Conesa et al. (2009), Bakış et al. (2015), Krueger and Ludwig (2016), and Heathcote et al. (2017), among others.

siderable errors in policy recommendations, resulting in sizable changes in marginal tax rates for both high- and low-income households. We also find that the welfare cost of parameter uncertainty is substantial. These findings underscore the importance of addressing parameter uncertainty to enhance policy design and achieve potential welfare gains.

The analysis in our paper begins with a theoretical section that establishes general conditions for understanding how parameter uncertainty qualitatively influences optimal tax policy. This theoretical analysis reveals a key insight: under parameter uncertainty, policymakers should adjust tax policy in a direction that increases the convexity of the welfare measure. The mechanism is analogous to precautionary savings due to prudence (Kimball 1990), where households respond to future consumption risk by saving more if the adjustment increases the convexity of future utility.[2] Similarly, policymakers can improve expected welfare by adopting a more progressive tax policy if it increases the convexity of the welfare measure with respect to the uncertain parameter. Additionally, we show that when multiple parameters are uncertain, their correlations also play a significant role in shaping the optimal policy. As an illustrative example, we present a tractable static model in which both uncertainty about labor supply elasticity and idiosyncratic wage risk lead to a more progressive optimal income tax policy.

Building on these theoretical insights, we quantify the effects of parameter uncertainty within a dynamic framework. We develop an incomplete-market life-cycle model of heterogeneous households with idiosyncratic wage risk and endogenous labor supply. This model serves two primary purposes: first, it enables us to interpret the data and assess uncertainty regarding key economic parameters; second, it acts as a laboratory for conducting thought experiments on tax reforms and evaluating their welfare consequences. We enhance the standard single-earner household model by explicitly incorporating the endogenous labor supply decisions of secondary earners (typically females), who play a vital role as a private insurance mechanism and significantly impact the optimal tax policy (Blundell et al. 2016;

[2] Specifically, the condition for precautionary saving behavior is that the third derivative of the utility function is positive. In this case, saving more raises average future consumption, leading to greater convexity of future utility with respect to future consumption.

Wu and Krueger 2021).

We focus on quantifying uncertainty related to the parameters that govern household preferences and wage processes, such as household risk aversion, labor supply elasticities, and the persistence and variance of wage shocks, among others. The level of uncertainty depends on the information that can be extracted from the available data. To assess this uncertainty, we estimate these parameters using a limited-information Bayesian approach.[3] Our analysis utilizes data from the 1999-2017 Panel Study of Income Dynamics (PSID), and through Bayesian inference, we obtain a joint posterior distribution of preference and wage parameters, effectively summarizing policymakers' uncertainty regarding these aspects of the economy.

To explore the tax policy implications of parameter uncertainty, as represented by the posterior distribution, we conduct thought experiments based on our life-cycle model, in which policymakers choose the income tax to maximize the welfare of a newborn cohort subject to a within-cohort budget constraint.[4] Following Bénabou (2002) and Heathcote et al. (2017), the income tax policy is characterized by two parameters of a nonlinear tax function $\widetilde{T}(Y) = Y - (1-\lambda)Y^{1-\tau}$, where Y is household income, $\widetilde{T}(Y)$ is tax liability, and τ and λ represent the progressivity and the level of income tax, respectively.

Policymakers face an equity-efficiency trade-off in tax policy decisions. A progressive income tax can reduce inequality and provide social insurance against idiosyncratic wage risks that are difficult to insure due to incomplete financial markets. However, the rising marginal tax rates associated with such a tax can discourage labor supply, leading to efficiency losses. Both the benefits and drawbacks of progressive taxation depend on underlying preference and wage parameters, which

[3]This approach can be viewed as the Bayesian version of the generalized method of moments (GMM), which offers several advantages. It quantifies parameter uncertainty by producing posterior distributions conditioned on observed data, in contrast to the frequentist approach, which provides distributions of estimators based on unknown true parameter values. Our limited-information approach also avoids the challenges of constructing full likelihood functions for complex nonlinear models by relying on data moments for parameter inference. Collectively, these features make our Bayesian approach a practical tool for assessing parameter uncertainty and its impact on optimal policy.

[4]We limit the optimal tax policy problem to a newborn cohort to avoid the complexities associated with redistributing income tax across different generations and the related question of how to weight them.

determine the optimal policy. When policymakers are uncertain about these parameters, they must balance the performance of tax policy and trade off welfare gains and losses across scenarios with different parameter values.

The main finding of our quantitative analysis is that accounting for uncertainty regarding preference and wage parameters results in a more progressive optimal income tax. This conclusion emerges from comparing two scenarios. In the first, consistent with the conventional literature, policymakers ignore parameter uncertainty and determine the optimal policy based on point estimates (i.e., expected values) of the parameters. In the second, policymakers account for parameter uncertainty by maximizing expected welfare based on the posterior distribution.[5] Our analysis shows that accounting for parameter uncertainty leads to the following changes in the optimal policy: the progressivity parameter τ increases by 0.021, from 0.128 to 0.148, while the level parameter λ decreases by 0.007, from 0.126 to 0.119. These adjustments correspond to an approximate 5.5 percentage-point increase in the marginal tax rate faced by high-income households relative to those at the bottom of the income distribution.

A decomposition exercise reveals that the increase in optimal tax progressivity is primarily driven by uncertainty about wage parameters, while uncertainty regarding preference parameters has a smaller, opposing effect. The larger impact of wage parameter uncertainty arises not only from greater uncertainty about these parameters but also from the higher sensitivity of optimal tax progressivity to this uncertainty. Through a similar decomposition, we find that most of the increase in tax progressivity results from uncertainty about male-related parameters, followed by female-related parameters and gender-neutral parameters.

Our quantitative analysis indicates that the welfare cost of uncertainty regarding preference and wage parameters is equivalent to 0.38% of household lifetime consumption, amounting to about 55 billion dollars per year based on 2019 U.S. consumption data, *through the income tax policy channel alone*.[6] We assess this

[5]We assume that policymakers treat parameter uncertainty as exogenous when choosing tax policy. Analyzing how policy decisions could influence the information available to policymakers—and, consequently, future uncertainty and policy choices—offers a promising avenue for future research.

[6]Contrary to the perception that this cost is trivial, it is worth noting that the welfare gain achiev-

cost by computing the welfare policymakers would be just willing to forgo for a signal revealing the true parameter values. Additionally, given that uncertainty about household preferences and wage processes is crucial not only for income tax policy but also for other government decisions, the total welfare cost of this uncertainty is likely even larger. Our findings suggest that enhancing our understanding of these economic aspects could yield substantial welfare gains.

The benchmark analysis in our paper assumes that government tax revenues are used to finance public consumption, which contributes to household utility. To ensure the robustness of our findings, we also consider alternative assumptions about government spending, including varying the rate of decline in the marginal utility of public consumption and imposing a balanced government budget in expectation with wasteful government spending. Our results show that the main findings remain robust under these alternative assumptions.

The analysis of parameter uncertainty in this paper offers several advantages over traditional sensitivity analysis, which typically involves repeating quantitative exercises for various parameter calibrations. A key limitation of sensitivity analysis is that it generates a parameter-contingent policy plan, which is unimplementable when policymakers lack precise knowledge of true parameter values. Additionally, parameter values in sensitivity analyses are often drawn from previous studies that may have used different assumptions inconsistent with the model employed for policy analysis. In contrast, our approach infers parameter uncertainty directly from the data within the context of the same model used for policy analysis. This results in a posterior distribution of parameters that also reflects the correlations between them, which we demonstrate are crucial for understanding both the qualitative and quantitative effects of uncertainty (Sections 2.1 and Appendix B.1).

The robust control framework (Hansen and Sargent 2008) provides an alternative approach to deal with model uncertainty. This approach is useful when statistical inference is difficult, and a posterior distribution of the true model cannot be quantified. As a result, the optimal policy is determined by solving a max-min prob-

able through optimal income taxation is typically of comparable magnitude. For instance, Heathcote et al. (2017) report a welfare gain of 0.6% of lifetime consumption using the same income tax function, underscoring the substantial impact of parameter uncertainty on welfare considerations in the context of income tax policy.

lem to guard against worst-case scenarios. Bhandari et al. (2024) and Vairo (2024) are two recent applications of the robust control approach to the optimal income tax question in stylized static environments. The former examines uncertainty about the shape of the labor productivity distribution's right tail and finds a less progressive optimal policy, while the latter studies uncertainty about households' ability to choose income distributions and finds the opposite—a more progressive optimal policy.

In contrast, we adopt a Bayesian perspective, using data to infer the posterior distribution of the model parameters and weighting scenarios accordingly, following Brainard (1967). We focus on parameter uncertainty as a natural extension of the quantitative Ramsey policy literature, emphasizing the incomplete nature of prior studies that fail to account for parameter uncertainty in policy design.[7] Unlike Bhandari et al. (2024) and Vairo (2024), we consider uncertainty about wage dynamics and household preferences, measured directly from the data,[8] and select the optimal policy balancing outcomes across scenarios, rather than focusing solely on worst-case outcomes. Our quantitative approach also enables us to simultaneously analyze uncertainties across various aspects of the economy within a dynamic model with realistic features such as endogenous precautionary savings and household labor supply. Given these key differences, our paper complements, rather than contradicts, Bhandari et al. (2024) and Vairo (2024), collectively advancing the understanding of how uncertainty shapes tax policy design.

Earlier research on the policy implications of parameter uncertainty has primarily focused on monetary policy. Notable quantitative studies include Levin et

[7]Although model misspecification is a relevant concern, it is difficult to quantify from the data. The robust control approach allows for model misspecification, but it is technically challenging to apply in a complex dynamic framework like our quantitative life-cycle model with uncertainty across multiple aspects of the economy. Our primary critique of the existing Ramsey literature is not the structural assumptions themselves, but rather, even if these assumptions are entirely accurate, prior analyses in the literature remain incomplete due to their omission of parameter uncertainty, which can be quantified from the data without further modeling assumptions.

[8]Although Bhandari et al. (2024) and Vairo (2024) examine uncertainty about an infinite-dimensional object (i.e., a continuous distribution), they do not quantify uncertainty from the data, which is difficult without parameterization assumptions. To achieve identification and measure uncertainty from the data, we parameterize our model and quantify uncertainty about a finite set of parameters using our Bayesian approach.

al. (2005) and Edge et al. (2010), which examine optimal monetary policy under parameter uncertainty within micro-founded New Keynesian models. In contrast, studies on the tax policy implications of parameter uncertainty are rare and mostly theoretical. For example, Lockwood et al. (2020) investigate optimal income tax design under uncertainty about the elasticity of taxable income in the Mirrleesian tradition, relying on a static framework.

The remainder of the paper is organized as follows: Section 2 presents theoretical insights into how parameter uncertainty affects optimal tax policy. Section 3 introduces the incomplete-market life-cycle model used for quantitative analysis. Section 4 outlines the empirical strategy for parameter estimation and summarizes the inferred parameter uncertainty. Section 5 explores tax reform counterfactuals and quantifies the implications of parameter uncertainty for tax policy. Finally, Section 6 concludes.

2 Theoretical Analysis

In this section, we derive general conditions that determine qualitatively how parameter uncertainty affects the optimal design of tax policy. We then illustrate the use of these conditions in a tractable static model, focusing on uncertainty about the elasticity of labor supply and the magnitude of idiosyncratic wage risk.

2.1 General Analysis

Without loss of generality, suppose that the tax policy is summarized by a single policy parameter τ that represents the progressivity of the tax schedule, and there is a single economic parameter θ that the policymakers are uncertain about. Let $W(\tau, \theta)$ denote the welfare gain from a tax reform that switches from the status quo policy to tax policy τ if the true value of the economic parameter is θ.

Policymakers have partial information about the economic parameter θ, and their posterior belief about its value is summarized by a probability distribution with the cdf $F_\theta(\theta)$. When uncertainty is ignored, policymakers treat the point estimate (i.e., expected value) of θ, $\bar{\theta} = \int \theta dF_\theta(\theta)$, as its true value and choose the tax policy

$\bar{\tau}$ to maximize the welfare gain $W(\tau, \bar{\theta})$:

$$\bar{\tau} = \arg\max_{\tau} W(\tau, \bar{\theta}).$$

When uncertainty is accounted for, policymakers should choose the optimal policy τ^* that maximizes the expected welfare gain $\widetilde{W}(\tau)$ based on the posterior distribution:

$$\tau^* = \arg\max_{\tau} \underbrace{\int_{\theta} W(\tau, \theta) dF_{\theta}(\theta)}_{\equiv \widetilde{W}(\tau)},$$

where policymakers are assumed to be risk-neutral with regard to the welfare risk induced by parameter uncertainty.

The question of interest here is how taking into account the uncertainty about θ affects the optimal tax policy, i.e., how different τ^* is from $\bar{\tau}$.[9] Let us first look at the uncertainty's effect on the welfare evaluation of tax reform. Suppose that the uncertainty about θ is small enough such that we can approximate the welfare gain function $W(\tau, \theta)$ by a second-order Taylor expansion at $\bar{\theta}$:

$$W(\tau, \theta) \approx W(\tau, \bar{\theta}) + W_{\theta}(\tau, \bar{\theta})(\theta - \bar{\theta}) + \frac{1}{2} W_{\theta\theta}(\tau, \bar{\theta})(\theta - \bar{\theta})^2,$$

where W_{θ} and $W_{\theta\theta}$ represent the first- and second-order partial derivatives of W with respect to θ. We can then write the expected welfare gain from tax reform $\widetilde{W}(\tau)$ as the sum of the welfare gain based on the point estimate $\bar{\theta}$ and an extra term capturing the effect of parameter uncertainty:

$$\widetilde{W}(\tau) = \int_{\theta} W(\tau, \theta) dF_{\theta}(\theta) \approx \underbrace{W(\tau, \bar{\theta})}_{\text{based on point estimate}} + \underbrace{\frac{1}{2} \sigma_{\theta}^2 W_{\theta\theta}(\tau, \bar{\theta})}_{\text{effect of uncertainty}}, \tag{1}$$

where $\sigma_{\theta}^2 = \int (\theta - \bar{\theta})^2 dF_{\theta}(\theta)$ is the variance of θ based on policymakers' posterior distribution. Therefore, the existence of parameter uncertainty implies a larger (smaller) welfare gain from the tax reform if $W_{\theta\theta}(\tau, \bar{\theta})$ is positive (negative), i.e.,

[9] Note that reparameterizing the model, such as using $x = \theta^{-1}$, will not affect the optimal policy accounting for parameter uncertainty, τ^*, but may alter $\bar{\tau}$ when uncertainty is ignored, potentially influencing the assessed effect of parameter uncertainty. See Appendix A.3 for details.

the welfare gain function is strictly convex (concave) in the uncertain parameter.

For the uncertainty's effect on optimal tax policy, from (1), we know that the slope of the expected welfare gain at $\bar{\tau}$ (the optimal tax progressivity based on the point estimate) is given by

$$\widetilde{W}'(\bar{\tau}) \approx \underbrace{W_\tau(\bar{\tau}, \bar{\theta})}_{=0} + \frac{1}{2}\sigma_\theta^2 W_{\theta\theta\tau}(\bar{\tau}, \bar{\theta}) = \frac{1}{2}\sigma_\theta^2 W_{\theta\theta\tau}(\bar{\tau}, \bar{\theta}),$$

where $W_\tau(\bar{\tau}, \bar{\theta})$ is the derivative of the welfare gain function with respect to tax progressivity evaluated at $\bar{\tau}$ based on the point estimate $\bar{\theta}$, and it equals zero because $\bar{\tau}$ maximizes $W(\tau, \bar{\theta})$ by definition. Hence the slope of the expected welfare gain function $\widetilde{W}'(\bar{\tau})$ is determined by the third-order derivative $W_{\theta\theta\tau}(\bar{\tau}, \bar{\theta})$, which reflects how the convexity of the welfare gain function $W_{\theta\theta}$ varies with tax progressivity τ. If it is positive (negative), the ex ante optimal policy τ^* that maximizes $\widetilde{W}(\tau)$ must be more (less) progressive than $\bar{\tau}$, as long as $\widetilde{W}(\tau)$ is single-peaked.

Proposition 1. *Under previous assumptions, accounting for parameter uncertainty leads to more (less) progressive optimal tax policy if welfare gain from tax reform becomes more (less) convex in the uncertain parameter as tax progressivity increases.*

To better understand this theoretical result, it is helpful to compare the response of optimal tax progressivity to parameter uncertainty here with the precautionary saving behavior of households in the literature since the mechanisms at work are similar. In the context of precautionary savings, households can reduce their utility loss from future consumption risk by increasing current savings in risk-free assets if household prudence is positive, i.e., the third-order derivative of the von Neumann-Morgenstern (vNM) utility function in consumption is positive (Kimball 1990). Notice that precautionary savings do not redistribute consumption across future states, and thus the benefit does not come from a reduction in absolute consumption risk. Instead, precautionary savings increase average future consumption, which shift the distribution of future consumption to an area of the vNM utility function with lower concavity. In other words, the benefit of precautionary savings is through reduction in absolute risk aversion.

Similarly, in the context of optimal policy response to parameter uncertainty, the welfare gain function $W(\tau,\theta)$ is equivalent to the vNM utility function, and its concavity with respect to the uncertain parameter, $-W_{\theta\theta}$, is equivalent to household risk aversion to consumption risk. In the presence of parameter uncertainty, a change in tax policy also cannot transfer resources across different parameter states, and policymakers cannot reduce the absolute parameter risk through tax policy. However, policymakers can still improve the expected welfare by adjusting tax progressivity if it can reduce the "risk aversion", i.e., the concavity of the welfare gain function. Consequently, the desirability of a more or less progressive tax policy in response to parameter uncertainty hinges on the third-order derivative $W_{\theta\theta\tau}$, just like the role of prudence for precautionary savings.

Proposition 1 summarizes the effect of parameter uncertainty when policymakers have limited information about a single parameter. What if there are multiple uncertain parameters? Let $\Theta = (\theta_i)_{i\in I}$ denote the vector of uncertain parameters. Then we can similarly approximate the expected welfare gain from a tax reform by

$$\widetilde{W}(\tau) \approx \underbrace{W(\tau,\bar{\Theta})}_{\text{based on point estimates}} \underbrace{+\frac{1}{2}\sum_{i,j\in I} W_{\theta_i\theta_j}(\tau,\bar{\Theta})\sigma_{\theta_i\theta_j}}_{\text{effect of uncertainty}},$$

where $\bar{\Theta}$ is the vector of expected values of parameters, $W_{\theta_i\theta_j}$ is the second-order derivative of W with respect to θ_i and θ_j, and $\sigma_{\theta_i\theta_j}$ is the covariance between θ_i and θ_j implied by the joint posterior distribution of Θ.

The slope of the expected welfare gain at $\bar{\tau}$ is then

$$\widetilde{W}'(\bar{\tau}) \approx \underbrace{W_\tau(\bar{\tau},\bar{\Theta})}_{=0} + \frac{1}{2}\sum_{i,j\in I} W_{\theta_i\theta_j\tau}(\bar{\tau},\bar{\Theta})\sigma_{\theta_i\theta_j} = \frac{1}{2}\sum_{i,j\in I} W_{\theta_i\theta_j\tau}(\bar{\tau},\bar{\Theta})\sigma_{\theta_i\theta_j}.$$

Following the previous logic, whether parameter uncertainty leads to more or less progressive optimal tax policy is determined by the sign of $\widetilde{W}'(\bar{\tau})$. However, different from the case with a single uncertain parameter, we can see that now in addition to the shape of the welfare gain function as reflected by the third-order derivatives $\{W_{\theta_i\theta_j\tau}(\bar{\tau},\bar{\Theta})\}_{i,j\in I}$, the covariances between uncertain parameters $(\sigma_{\theta_i\theta_j})_{i,j\in I}$ implied by the posterior distribution also matter to even the sign of the uncertainty's effect. This suggests that a proper construction of the joint posterior distribution is important for both qualitative and quantitative evaluations about the effects of parameter uncertainty, which is exactly the goal of our Bayesian inference in Section 4.

2.2 Lessons from the Static Model

We now present a static model with standard preferences, for which we can derive the welfare gain function in closed form. We then apply the general conditions from Section 2.1 to determine qualitatively the implications of uncertainty about key economic parameters, namely, the elasticity of labor supply and the magnitude of idiosyncratic wage risk, on progressive income taxation.[10]

Consider a static economy populated by a continuum of measure one households. Households differ in their labor productivity z, which follows a log-normal distribution $LN(-\frac{1}{2}\sigma_z^2, \sigma_z^2)$ in the population. Note that the average productivity is always 1, and σ_z only affects the dispersion of the productivity distribution. Each household chooses labor supply H and consumption C to maximize its utility subject to the household budget constraint:

$$\max_{\{C,H\}} \ln C - \frac{H^{1+\eta^{-1}}}{1+\eta^{-1}} + \gamma \ln G$$

s.t.

$$C = zH - \widetilde{T}(zH),$$

where η is the Frisch elasticity of labor supply, G is government spending on public consumption, and $\widetilde{T}(\cdot)$ is the income tax function. Following Bénabou (2002) and Heathcote et al. (2017), we set

$$\widetilde{T}(zH) = zH - (1-\lambda)(zH)^{1-\tau},$$

[10] Our static model is a simplified version of the model in Heathcote et al. (2017), adding parameter uncertainty. Although the original model of Heathcote et al. (2017) permits a nice closed-form formula for the welfare gain from tax reform without parameter uncertainty, it is no longer the case for the expected welfare gain with parameter uncertainty. Appendix A.4 explores along this direction and illustrates the key difficulty.

where λ controls the tax level, and τ governs the tax progressivity. Let $H(z;\tau,\lambda)$ denote the labor supply of productivity z household under policy (τ,λ). The amount of public consumption $G(\tau,\lambda)$ is determined by the government budget constraint:

$$G(\tau,\lambda)=\int_z \widetilde{T}\left(zH(z;\tau,\lambda)\right)dF_z(z),$$

where $F_z(z)$ is the cdf for productivity z.

Policymakers are uncertain about the labor supply elasticity and the amount of idiosyncratic risk, i.e., the uncertain parameters are $\Theta=(\eta,\sigma_z)$. For tractability, we assume that policymakers must choose the tax progressivity τ before parameter uncertainty is resolved, whereas the tax level λ is chosen ex post contingent on the tax progressivity and the true parameter values to maximize the ex post welfare.[11] This simplifying assumption allows us to substitute λ with τ based on the ex post optimality condition, and therefore, we focus on the choice of tax progressivity τ in the following discussion.

Suppose that the status quo income tax is flat, i.e., $\tau_{sq}=0$,[12] and policymakers are utilitarian. Appendix A.1 shows that the social welfare gain from adopting tax progressivity τ can be expressed in closed form as

$$\Delta(\tau,\Theta)\equiv\underbrace{\frac{1}{2}\sigma_z^2\tau(2-\tau)}_{\text{insurance benefit}}+\underbrace{\frac{1}{1+\eta^{-1}}\left[(1+\gamma)\ln(1-\tau)+\tau\right]}_{\text{efficiency cost}}.$$

The first part of the formula captures the insurance benefit of progressive income tax against idiosyncratic wage risk, and the second part reflects the efficiency cost of progressive taxation through distorting household labor supply decisions. More specifically, a more progressive income tax discourages labor supply, which reduces the total output ($\ln(1-\tau)$ part) and labor disutility ($+\tau$ part). The insurance benefit is increasing in the amount of idiosyncratic risk σ_z, and the efficiency cost is amplified

[11]This assumption is relaxed in our quantitative analysis in Section 5. As a robustness check, we relax this assumption in the static model and confirm numerically that imposing or omitting the timing assumption does not alter the conclusions in this section when calibrated to empirically plausible values. Numerical results are available upon request.

[12]The status quo tax level is $\lambda_{sq}=\frac{\gamma}{1+\gamma}$, which is optimal given $\tau_{sq}=0$ and independent of parameter Θ.

by labor supply elasticity η. Hence the values of these two parameters directly affect the equity-efficiency trade-off faced by policymakers.

One important issue here is that $\Delta(\tau, \Theta)$ is in household indirect utility, and hence it may not be comparable across different parameter states, especially when there is uncertainty about household preferences. To address this issue, we measure the welfare gain from a tax reform in each parameter state by the consumption equivalent variation, i.e., the amount of consumption transfers required to generate the same welfare gain as the tax reform. Following the convention, we set the consumption transfers to be proportional to household consumption before the tax reform, and given the log utility in consumption, the welfare gain in consumption equivalent variation is

$$W(\tau, \Theta) \equiv \int_z (e^{\Delta(\tau,\Theta)} - 1) C_{sq}(z) dF_z(z) = \left(e^{\Delta(\tau,\Theta)} - 1\right) \frac{1}{1+\gamma},$$

where $C_{sq}(z) = \frac{z}{1+\gamma}$ is the consumption of productivity z households under the status quo tax policy.

Let $\bar{\Theta} = (\bar{\eta}, \bar{\sigma}_z)$ denote the expected values of η and σ_z based on policymakers' posterior belief, and $\bar{\tau}$ denote the policy that maximizes the welfare when uncertainty is ignored, i.e, $W(\tau, \bar{\Theta})$. Appendix A.2 shows that when $\bar{\tau} \in (0, 1)$ and $\gamma > 0$, we have $W_{\eta\eta\tau}(\bar{\tau}, \bar{\Theta}) > 0$ and $W_{\sigma_z\sigma_z\tau}(\bar{\tau}, \bar{\Theta}) > 0$. Applying the results from Section 2.1, we know that uncertainty about the elasticity of labor supply and the magnitude of idiosyncratic wage risk leads to more progressive optimal income tax. For simplicity, we assume here that there is no correlation between the value of η and σ_z based on policymakers' belief, i.e., $\sigma_{\eta\sigma_z} = 0$. We will allow correlations between uncertain parameters in our quantitative analysis.

Intuitively, since the efficiency cost of more progressive income tax is concave in labor supply elasticity, uncertainty about the elasticity lowers the expected efficiency cost following Jensen's inequality, which then implies a more progressive optimal tax policy. Similarly, the insurance benefit of more progressive income tax is convex in the magnitude of wage risk, and hence the expected insurance benefit is higher when the magnitude of wage risk is uncertain, and the optimal tax policy also becomes more progressive.

3 The Quantitative Life-Cycle Model

The sharp theoretical prediction of the static model in Section 2.2 comes at the cost of abstracting away from some aspects of reality important for tax policy consideration, for example, household life cycle and endogenous private insurance through precautionary savings and family labor supply. To provide a quantitative examination of uncertainty's effect on tax policy, a richer model augmented with these additional features is called for. Our analysis will focus on policymakers' uncertainty about household preferences and idiosyncratic wage process because there is, arguably, more consensus on model specification, and parameter uncertainty is of major concern for tax policy decisions.[13]

In this section, we present the quantitative dynamic model, through which we interpret the data and measure uncertainty about preference and wage parameters. The model also serves as a laboratory for conducting thought experiments of tax reforms and evaluating their welfare consequences. We first describe the physical environment of our model, then state the household optimization problem in its recursive representation, and finally formulate the optimal tax problem under parameter uncertainty.

3.1 Environment

We study a partial equilibrium life-cycle model with idiosyncratic wage risk and endogenous labor supply. We follow a cohort of a continuum of measure one households over their life cycle. These households live for T periods, from age 1 to T, work in the first R periods of life, and then are retired from age $R+1$ onward. Each household consists of two members: a male and a female. For simplicity,

[13]In contrast, we do not model explicitly certain factors (e.g. endogenous skill accumulation) in our quantitative model because i) there is greater uncertainty about the mechanism (e.g., learning-by-doing or on-the-job-training) than uncertainty about related parameters, and ii) there are often identification issues without proper data (e.g., Heckman et al. 2002). Hence we take a more agnostic approach and try to account for their effects on tax policy later through the Pareto weights in the optimal tax policy problem (details in Section 5). Also, taking into account parameter uncertainty in the policymaking problem requires numerical integration with respect to the multivariate posterior distribution of parameters, which increases the computation burden significantly compared to the standard optimal tax policy exercises in the literature. Therefore, keeping the model to the point helps mitigate this challenge.

we omit the index for different households and denote by $X_{j,t}$ the variable X of member j at age t, with $j = 1$ or 2 indicating the male or the female member.

Households enjoy joint consumption C_t and choose the labor supply of both members $H_{1,t}$ and $H_{2,t}$ that incur disutility. The period utility function is given by $u(C_t, H_{1,t}, H_{2,t})$. An operative extensive margin of female labor supply is included in the model by introducing a fixed per-period utility cost f whenever female hours worked are strictly positive. Households discount the future utility at the constant rate δ, so that $1/(1+\delta)$ is the household time discount factor.

Members of a household can work at wages $W_{j,t}$ determined by their labor productivity. Log-wages of both household members are stochastic and represent the sum of i) a deterministic life-cycle component $g_{j,t}$ that is common across households, ii) an idiosyncratic permanent component α_j, and iii) an idiosyncratic persistent component $F_{j,t}$:

$$\ln W_{j,t} = g_{j,t} + \alpha_j + F_{j,t}. \tag{2}$$

Both the permanent component α_j and the initial value of the persistent component $F_{j,1}$ are drawn randomly at age 1, and they may be correlated between the two members of each household, i.e.,

$$\begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} \sim N\left(0, \begin{bmatrix} \sigma^2_{\alpha_1} & \sigma_{\alpha_1,\alpha_2} \\ \sigma_{\alpha_1,\alpha_2} & \sigma^2_{\alpha_2} \end{bmatrix}\right),$$

and

$$\begin{bmatrix} F_{1,1} \\ F_{2,1} \end{bmatrix} \sim N\left(0, \begin{bmatrix} \sigma^2_{F_{1,1}} & \sigma_{F_{1,1},F_{2,1}} \\ \sigma_{F_{1,1},F_{2,1}} & \sigma^2_{F_{2,1}} \end{bmatrix}\right),$$

where σ^2_x and $\sigma_{x,y}$ denote the variances and covariance of joint normal distribution. The permanent component remains constant over household life cycle, whereas the persistent component $F_{j,t}$ follows an AR(1) process with persistence ρ_j:

$$F_{j,t} = \rho_j F_{j,t-1} + v_{j,t}. \tag{3}$$

Here $v_{j,t}$ is the normally distributed random shock to member j's wage at age t, and they may be correlated between two members of the same household, but are independent over time and across different households:

$$\begin{bmatrix} v_{1,t} \\ v_{2,t} \end{bmatrix} \sim N\left(0, \begin{bmatrix} \sigma^2_{v_1} & \sigma_{v_1,v_2} \\ \sigma_{v_1,v_2} & \sigma^2_{v_2} \end{bmatrix}\right),$$

where $\sigma^2_{v_1}$, $\sigma^2_{v_2}$, and σ_{v_1,v_2} are the variances and covariance of male and female wage shocks. Note that both the deterministic component and the parameters governing the idiosyncratic components are gender-specific.

As is common in standard incomplete-market models, households cannot trade fully state-contingent Arrow securities, but they can save, and potentially borrow, at the risk-free interest rate r subject to a borrowing limit $\underline{A}$.[14] Working-age households need to pay income and payroll taxes in each period, and retired households are eligible for a fixed amount of retirement benefit b in each period in which she is alive.[15]

3.2 Household Optimization Problem

The state variables of a working-age household include the current savings A, the male and female persistent wage components, F_1 and F_2, the age of the household t, and the permanent wage components, α_1 and α_2. In each period, members of each household make joint decisions on household consumption C, savings for the next period A', and labor supply of both members H_1 and H_2 to maximize their discounted utility subject to the budget constraint. A working-age household's problem is then, in recursive form:

$$\begin{aligned} V(A, F_1, F_2, t, \alpha_1, \alpha_2) = \max_{\{C, A', H_1, H_2\}} & u(C, H_1, H_2) - \mathbf{I}(H_2 > 0)f \\ & + \frac{1}{1+\delta} \mathbb{E}_{(F_1', F_2')} \left[V(A', F_1', F_2', t+1, \alpha_1, \alpha_2) | F_1, F_2 \right] \\ \text{s.t.} \quad & C + A' = Y - \widetilde{T}(Y) - \tau_{ss} Y + (1+r)A, \end{aligned}$$

[14] Households are born with zero savings.

[15] The U.S. social security benefits are piecewise linear functions of average monthly past earnings over the working life. Additional rules govern benefits for spouses. A full representation of the U.S. social security system is costly in terms of computation, since it adds two continuous state variables to the recursive formulation of the problem. Hence we model the U.S. social security benefit formula starkly, by assuming that the benefits per household are independent of past contributions.

$$
\begin{aligned}
&Y = W_{1,t}H_1 + W_{2,t}H_2, \\
&C, H_1, H_2 \geq 0,\ A' \geq \underline{A},
\end{aligned}
$$

where $\mathbf{I}(H_2 > 0)$ equals 1 if female hours H_2 is positive. Female hours of $H_2 = 0$ corresponds to non-participation. The term $\widetilde{T}(Y)$ in the budget constraint is the income tax function that determines the tax liability of a household with before-tax income Y, and τ_{ss} is a flat payroll tax representing the Federal Insurance Contribution Act (FICA) taxes. The wage of each member $W_{j,t}$ is determined by household states F_j, t, and α_j according to (2).

After retirement, labor productivity falls to zero, and hence households optimally do not work in retirement. The state variables of retired households reduce to only current savings and the age of the household. The dynamic programming problem of a retired household is then:

$$
\begin{aligned}
V^R(A,t) = &\max_{\{C,A'\}} u(C,0,0) + \frac{1}{1+\delta} V^R(A', t+1) \\
\text{s.t.} \quad & C + A' = b + (1+r)A, \\
& C \geq 0,\ A' \geq \underline{A}.
\end{aligned}
$$

Households are assumed to have an additively separable utility function of the form:

$$
u(C, H_1, H_2) = \frac{C^{1-\sigma}}{1-\sigma} - \psi_1 \frac{H_1^{1+\eta_1^{-1}}}{1+\eta_1^{-1}} - \psi_2 \frac{H_2^{1+\eta_2^{-1}}}{1+\eta_2^{-1}}.
$$

The advantage of using this preference structure is that all the preference parameters are directly interpretable. The parameter σ governs household risk aversion, and its reciprocal is the Frisch elasticity of consumption with respect to its own price. The parameters η_1 and η_2 are the Frisch elasticities of male and female labor supply with respect to their own wages, and ψ_1 and ψ_2 control the levels of disutility from male and female labor supply.

3.3 The Optimal Tax Problem

We now describe the optimal tax problem faced by policymakers in this model economy. Consistent with both the Ramsey optimal tax literature and real-world practice, policymakers are restricted to taxing households based on their earnings rather than their productivities or wages.[16] Policymakers are assumed to know the structure of the model, including the wage process and household utility function, but remain uncertain about the values of key model parameters. Consequently, they select an income tax policy based on their belief about the distribution of these parameters to maximize expected social welfare. Once household decisions are realized based on the true parameter values, the government observes the resulting revenue and uses it to finance public consumption.

Before choosing the tax policy, policymakers can use historical data to learn about the parameters and form beliefs about their distribution. We focus on once-and-for-all tax reforms, where the tax policy remains fixed after the reform. Due to computational constraints, we do not consider scenarios where policymakers continuously update their beliefs and adjust tax policy over time, as this would require tracking the entire distribution of parameters as part of the state space in their decision-making problem. Addressing this limitation is an important direction for future research.

We allow the income tax function $\widetilde{T}(Y)$ to be progressive and adopt the same two-parameter tax function as in the static model:

$$\widetilde{T}(Y) = Y - (1 - \lambda)Y^{1-\tau}, \tag{4}$$

where τ and λ are two parameters governing the progressivity and the level of the income tax, respectively. It implies that after-tax income $Y - \widetilde{T}(Y)$ is an increasing and concave function of pre-tax income Y. Tax policy is thus represented by the two parameters of the income tax function, τ and λ.

Policymakers' uncertainty about model parameters is summarized by a posterior distribution $\Pi(\Theta)$, where Θ represents the vector of parameters governing household preferences and wage process. Let $W(\tau, \lambda, \Theta)$ denote the objective function of policymakers if they know Θ for sure, the (ex ante) optimal tax policy (τ^*, λ^*) is

[16] While we do not take a definitive stance on why this holds in practice, one possible explanation, as in the Mirrlees mechanism design approach to optimal taxation, is that the government observes earnings but not hours worked, making individual productivity private information.

then given by

$$(\tau^*, \lambda^*) = \arg\max_{(\tau,\lambda)} \Gamma^{-1}\left(\int_\Theta \Gamma\left(W(\tau, \lambda, \Theta)\right) d\Pi(\Theta)\right), \tag{5}$$

where $\Gamma(\cdot)$ is a strictly increasing function reflecting the risk preferences of policymakers. The inverse function $\Gamma^{-1}(\cdot)$ outside converts the policymakers' "utility" to its certainty equivalent value. For our benchmark analysis, policymakers are assumed to be risk-neutral, i.e., $\Gamma(\cdot)$ is linear. We investigate the implications of policymakers' risk aversion in Appendix B.2.

Given parameter Θ, policymakers' goal is simply to maximize the welfare gain from adopting the new policy (τ, λ), i.e., $W(\tau, \lambda, \Theta)$. Since policymakers are uncertain about the true value of Θ when choosing the tax policy, they must trade off welfare gains and losses across parameter states in which household preferences differ. Hence to make such comparison meaningful, we measure $W(\tau, \lambda, \Theta)$ in consumption equivalent variations. More specifically, suppose that the social welfare function $\mathrm{SWF}(\tau, \lambda, \Theta)$ is given by a weighted sum of household welfare for a newborn cohort:[17]

$$\mathrm{SWF}(\tau, \lambda, \Theta) = \int_{\mathbf{s}} \omega(\mathbf{s}) \widetilde{V}_1(\mathbf{s}; \tau, \lambda, \Theta) d\Phi_1(\mathbf{s}), \tag{6}$$

where $\mathrm{s} = \{A, F_1, F_2, \alpha_1, \alpha_2\}$ is the vector of household states except age, $\omega(\mathbf{s})$ is the Pareto weight function, $\widetilde{V}_1(\mathbf{s}; \tau, \lambda, \Theta)$ is the expected lifetime utility of a newborn (i.e., age 1) household, and $\Phi_1(\mathbf{s})$ is the distribution of newborn households. $W(\tau, \lambda, \Theta)$ is then defined as the total amount of consumption transfers required to achieve the same social welfare change as adopting tax policy (τ, λ), i.e., $\mathrm{SWF}(\tau, \lambda, \Theta) - \mathrm{SWF}(\tau_{sq}, \lambda_{sq}, \Theta)$, where $(\tau_{sq}, \lambda_{sq})$ denotes the status quo tax policy (more details in Appendix C.2).

In our benchmark analysis, we assume that tax revenue finances public consumption, which enters household utility in an additively separable manner. Specif-

[17] We choose the welfare measure for a newborn cohort to avoid the redistribution motive of tax policy over different cohorts and hence the need to take a stand on how to weight different generations.

ically, the expected lifetime utility $\widetilde{V}_1(\mathbf{s};\tau,\lambda,\Theta)$ is given by:

$$\widetilde{V}_1(\mathbf{s};\tau,\lambda,\Theta) \equiv V_1(\mathbf{s};\tau,\lambda,\Theta) + \gamma\frac{[G(\tau,\lambda,\Theta)]^{1-\sigma_G}-1}{1-\sigma_G}. \tag{7}$$

Here $V_1(\mathbf{s};\tau,\lambda,\Theta)$ is the value function of a newborn household defined by the household optimization problem in Section 3.2, which combines utility from private consumption and labor disutility. $G(\tau,\lambda,\Theta)$ denotes the amount of public consumption, which is financed by tax revenues from the same cohort:

$$G(\tau,\lambda,\Theta) = \sum_{t=1}^{R}\frac{\mathrm{Tax}_t(\tau,\lambda,\Theta)}{(1+r)^{t-1}},$$

$$\mathrm{Tax}_t(\tau,\lambda,\Theta) = \int_{\mathbf{s}}\widetilde{T}(Y_t(\mathbf{s};\tau,\lambda,\Theta))d\Phi_t(\mathbf{s};\tau,\lambda,\Theta),\ t=1,\ldots,R,$$

where $Y_t(\mathbf{s};\tau,\lambda,\Theta)$ is household income, $\Phi_t(\mathbf{s};\tau,\lambda,\Theta)$ is the distribution of households, and $\mathrm{Tax}_t(\tau,\lambda,\Theta)$ is the tax revenue, all for age-t households. Public consumption benefits all households equally, and γ is the parameter that controls the taste for public consumption relative to private consumption, and σ_G governs how fast the marginal utility of public consumption declines with its level. We conduct sensitivity analysis regarding alternative assumptions about government spending and budget constraint in Section 5.3.

4 Measure Uncertainty from the Data

In this section, we take the model in Section 3 to the U.S. data and quantify the degree of uncertainty about parameters governing household preferences and idiosyncratic wage process. We first describe the main data set used for our empirical analysis and how we choose the values of externally calibrated parameters. We then provide a brief summary of the limited-information Bayesian method that we employ to estimate the preference and wage parameters. After that, we explain our estimation strategy and report the estimation results. Finally, we assess the goodness of fit of our model.

4.1 The Data

Our main data source is the core sample of the 1999-2017 Panel Study of Income Dynamics (PSID), from which we obtain individual and household level information about earnings, hours worked, consumption, net worth, and characteristics such as age, race, education, number of children, and so on.[18] The longitudinal structure of the PSID allows us to follow the same individuals and households over time (i.e., every two years) and observe the comovement in these variables, which is crucial for our estimation strategy.[19] We focus on married households with working male head aged between 30 and 57 because this group of households fit best the specification of our life-cycle model and represent the majority of the U.S. population. To ease the burden of computation, we set each period in our life-cycle model to four years in the data, and hence the biennial PSID data are converted to four-year frequency. Wages are constructed as earnings divided by hours worked.

All nominal variables are converted to values in year 2000 U.S. dollars based on the consumer price index for all urban consumers (CPI-U) from the U.S. Bureau of Labor Statistics. We set the units of income and labor supply in our model to the average four-year earnings and hours worked by males in our PSID sample, which are \$243,766 and 9,202 hours (i.e., \$60,942 and 2301 hours per year), respectively.

4.2 External Calibration

Before estimating the preference and wage parameters, we first calibrate the other parameters outside of the life-cycle model, and their values are reported in Table 1. The key difference between these calibrated parameters and the estimated ones is that the former are either directly observable or can be inferred with few to no model assumptions.

[18] We follow closely the procedures in Blundell et al. (2016) when constructing variables from the PSID data and identifying outliers.

[19] The top coding of the PSID leads to a modest underrepresentation of top income inequality compared to the Survey of Consumer Finance (Gaillard et al. 2023). However, since panel data are crucial to our empirical strategy, we rely on the PSID data despite this limitation. Bhandari et al. (2024) provides a more detailed examination of the income tax implications of uncertainty surrounding the shape of the right tail.

4.2.1 Demographic

As mentioned earlier, one period in the model represents four years in the data. We consider the part of household life cycle between age 22 and age 81 with a retirement age of 65. This then translates to a life cycle in the model from age 1 to $T = 15$ with a retirement age of $R = 11$.

4.2.2 Income Tax

There are two parameters in the income tax function given by (4): τ for the income tax progressivity and λ for the income tax level. We estimate these two parameters by taking the natural log of (4) and running the following OLS regression with our PSID sample:

$$\ln(Y - \widetilde{T}(Y)) = \ln(1 - \lambda) + (1 - \tau)\ln(Y).$$

Tax liability $\widetilde{T}(Y)$ is defined as federal income tax minus earned income tax credit (EITC) and food stamp benefits. Federal income tax and EITC are calculated based on household income Y and the actual income tax code, and food stamp benefits are obtained directly from the PSID. The estimated income tax parameters are $\tau = 0.128$ and $\lambda = 0.126$, with standard error 0.002 and 0.001, respectively.

4.2.3 Payroll Tax and Retirement Benefit

The flat payroll tax rate τ_{ss} is set to 7.65%, based on the Federal Insurance Contribution Act (FICA) tax rates on pre-tax income of employees. The retirement benefit b in the model corresponds to the sum of Social Security benefits and benefits from Medicare. We calibrate the Social Security benefits to the sum of average benefits received by males and females aged 66 and older in the 1999-2017 Annual Social and Economic Supplement (ASEC) of the Current Population Survey (CPS), given by \$20,975 per year in 2000 dollars. Since the benefits from Medicare are difficult to measure directly, we assume that they are proportional to the social security benefits, based on the ratio of Medicare tax rate to Social Security tax rate. Therefore, the retirement benefit b in the model is calibrated to $\$20,975 \times 7.65\%/6.2\% \times 4 = \$103,522$, i.e., 0.425 in model income units.

4.2.4 Wage Trend

For the deterministic life-cycle component of log-wage, $g_{j,t}$ in (2), we regress the male or female log-wage on a quadratic polynomial in age, together with a group of controls for the year, education, race, and location, etc. The gender-specific age-profiles of log-wage are then constructed as the predicted values from these regressions at different ages while integrating over the remaining covariates. The resulting wage trends are presented in Figure 9 of Appendix C.

4.2.5 Interest Rate and Borrowing Limit

We set the annual risk-free interest rate at 2%, which implies a four-year interest rate of $r = 8.24\%$. We exclude non-collateralized debts in the model by imposing a zero borrowing limit (i.e., $\underline{A} = 0$).[20]

Table 1: Externally Calibrated Parameters

Parameter	Description	Value
T	length of life cycle	15
R	retirement age	11
τ	income tax progressivity	0.128
λ	income tax level	0.126
τ_{ss}	payroll tax rate	7.65%
b	retirement benefit	0.425
r	real interest rate	8.24%
$\underline{A}$	borrowing limit	0

Notes: Each period in the model corresponds to four years in the data.

4.3 Bayesian Inference

We estimate the remaining parameters about household preferences and idiosyncratic wage process using the PSID data through a limited-information Bayesian approach and quantify the uncertainty about these parameters by the posterior distribution.

[20]Since we focus on households aged 30-57, who often have significantly positive net worth, the zero-borrowing-limit assumption is inconsequential to our results.

4.3.1 The Limited-Information Bayesian Method

The limited-information Bayesian method, as described in Kim (2002) and later advocated by Christiano et al. (2010) and Fernández-Villaverde et al. (2016) among others, can be viewed as the Bayesian version of the generalized method of moments (GMM). Similar to GMM, the limited-information Bayesian method only uses a set of moments from the data for parameter inference, and therefore, it does not require strong distributional assumptions about the error terms in the model of the data generating process. There are two main reasons why we adopt the limited-information Bayesian method for our empirical analysis. First, a proper characterization of parameter uncertainty requires the distribution of parameters conditional on the information we already have (e.g., the data we observe), which is conveniently the output of Bayesian inference.[21] Second, the full likelihood function is difficult to construct for a complex nonlinear model like ours, whereas the limited-information Bayesian method allows us to sidestep this obstacle.

Let Θ denote the parameters of interest and $\hat{\mathbf{m}}$ denote the vector of M empirical moments from the data for estimation. Kim (2002) shows that the likelihood of $\hat{\mathbf{m}}$ conditional on Θ is approximately

$$f(\hat{\mathbf{m}}|\Theta) = (2\pi)^{-\frac{M}{2}} |S|^{-\frac{1}{2}} \exp\left[-\frac{1}{2}\left(\hat{\mathbf{m}} - \mathbf{m}(\Theta)\right)' S^{-1} \left(\hat{\mathbf{m}} - \mathbf{m}(\Theta)\right)\right], \tag{8}$$

where $\mathbf{m}(\Theta)$ is the model's prediction for the moments under parameter Θ, and S is the covariance matrix of $\hat{\mathbf{m}}$. The covariance matrix S is often unknown but can be replaced by a consistent estimator of it, which can be obtained through bootstrap. Bayes' theorem tells us that the posterior density $f(\Theta|\hat{\mathbf{m}})$ is proportional to the product of the likelihood $f(\hat{\mathbf{m}}|\Theta)$ and the prior density $p(\Theta)$:

$$f(\Theta|\hat{\mathbf{m}}) \propto f(\hat{\mathbf{m}}|\Theta)p(\Theta), \tag{9}$$

and we can then apply the standard Markov Chain Monte Carlo (MCMC) techniques such as the Metropolis-Hastings algorithm to obtain a sequence of random

[21] In contrast, the standard GMM produces estimators for parameters as functions of the data with distributions conditional on the true values of parameters.

samples from the posterior distribution.

4.3.2 Estimation Strategy

Except the Bayesian approach, we follow closely the empirical strategy in Blundell et al. (2016). In particular, using the PSID data, we first regress wage, consumption, and earnings growth on observable characteristics of individuals and households and obtain the residuals $\Delta w_{j,t}$, Δc_t, and $\Delta y_{j,t}$, respectively. Additionally, by regressing log wages of young households on observable characteristics, we decompose initial wages into a component explained by household characteristics $\hat{w}_{j,1}$, and an unexplained residual $w_{j,1}$.

Similar to Blundell et al. (2016), we then estimate the eleven wage parameters (ρ_1, ρ_2, $\sigma^2_{v_1}$, $\sigma^2_{v_2}$, $corr_{v_1,v_2}$, $\sigma^2_{F_{1,1}}$, $\sigma^2_{F_{2,1}}$, $corr_{F_{1,1},F_{2,1}}$, $\sigma^2_{\alpha_1}$, $\sigma^2_{\alpha_2}$, $corr_{\alpha_1,\alpha_2}$) using a group of second-order moments of $\Delta w_{j,t}$, $\hat{w}_{j,1}$, and $w_{j,1}$. The moments of $\Delta w_{j,t}$ identify the parameters governing the dynamics of the persistent wage component, while the moments of $\hat{w}_{j,1}$ and $w_{j,1}$ pin down the covariance matrices of the permanent wage component and the initial values of the persistent component, respectively. Notably, the estimation of wage parameters relies solely on the statistical model of wage process and is immune to our assumptions regarding the life-cycle model.[22] Given the estimates of wage parameters, we then combine a group of second-order moments of $\Delta w_{j,t}$, Δc_t, and $\Delta y_{j,t}$ and a group of first-order moments of earnings, hours worked, female participation, and household net worth to estimate jointly the seven preference parameters (σ, η_1, η_2, ψ_1, ψ_2, f, δ).[23] Blundell et al. (2016) show that the second-order moments identify the elasticity parameters (σ, η_1, η_2), and the remaining preference parameters are pinned down by the first-order moments. The list of moment conditions that we employ in our estimation are provided in Table 9 of Appendix C.

When constructing the likelihood in (8) for Bayesian estimation, the estimate of the covariance matrix S is obtained from 5,000 bootstrap samples of the PSID data, and the model predicted moments $\mathbf{m}(\Theta)$ are computed based on a model-simulated

[22] We estimate the correlation coefficient between male and female wage shocks or components $corr_{x_1,x_2}$ instead of the covariance σ_{x_1,x_2}.

[23] Note that we do not need to adjust the empirical moments for sample selection due to endogenous female participation decisions since our structural model also features an operative extensive margin of female labor supply that is disciplined by the data.

panel of 50,000 households.[24] We adopt an uninformative prior $p(\Theta)$ consisting of independent uniform distributions of each parameter. We apply the random-walk Metropolis-Hastings algorithm to simulate draws from the posterior density $f(\Theta|\hat{\mathbf{m}})$ given by (9), and the posterior distribution is characterized by a sequence of 15,000 draws after a burn-in of 5,000 draws.

4.3.3 Estimation Results

Table 2 reports the posterior means and the 95% credible intervals of preference and wage parameters from the Bayesian estimation, together with the uniform priors. For the posterior means, one interesting result is that our estimate of the Frisch elasticity of female labor supply η_2 is somewhat lower than the male counterpart η_1. The reason is partly because we allow gender-specific persistence of wage shocks and find that female shocks are significantly less persistent than male shocks (0.766 vs. 0.928). This difference reduces the income/wealth effect of female wage shocks, and hence a weaker substitution effect (i.e., a lower elasticity of labor supply) for females is enough to explain the variations of female earnings in the data. The 95% credible intervals of the posterior distributions are much narrower than the uniform priors, suggesting that the uncertainty about these parameters is greatly reduced by the information contained in the data.

Figure 1 plots the posterior distributions of each preference and wage parameter. Notice that the posterior distributions are not necessarily normal or symmetric. Both Table 2 and Figure 1 are about the marginal distributions of parameters, but since these parameters are estimated jointly, they may be correlated in the posterior distribution. Table 10 and 11 of Appendix C report the correlations among preference and wage parameters, respectively. In general, the correlations among preference parameters are stronger than those among the wage parameters.

[24]For consistency, we add measurement errors to model-simulated data as well. Like Blundell et al. (2016), the standard deviation of measurement errors on log-consumption is set to 0.20 based on the data moment $\mathbb{E}(\Delta c_t \Delta c_{t-1})$. For log-earnings and log-hours, the standard deviations of measurement errors are set to 0.15 following the literature.

Table 2: Estimated Parameters

Parameter	Description	Posterior Distribution Mean	Posterior Distribution 95% Interval	Uniform Prior [Min, Max]
A. Preference Parameters				
σ	household risk aversion	2.595	[2.216, 3.050]	[1.001, 6.000]
η_1	male labor supply elasticity	0.312	[0.231, 0.393]	[0.001, 2.000]
η_2	female labor supply elasticity	0.239	[0.183, 0.313]	[0.001, 2.000]
ψ_1	disutility of male labor supply	0.933	[0.849, 1.041]	[0.010, 5.000]
ψ_2	disutility of female labor supply	3.311	[2.232, 4.677]	[0.010, 5.000]
f	fixed utility cost of female participation	0.145	[0.126, 0.161]	[0.001, 0.500]
δ	discount rate of utility	0.024	[0.017, 0.031]	[-0.100, 0.100]
B. Wage Parameters				
ρ_1	persistence of male wage shocks	0.928	[0.809, 1.015]	[0.100, 1.200]
ρ_2	persistence of female wage shocks	0.766	[0.609, 0.930]	[0.100, 1.200]
$\sigma^2_{v_1}$	variance of male wage shocks	0.074	[0.065, 0.082]	[0.010, 0.300]
$\sigma^2_{v_2}$	variance of female wage shocks	0.085	[0.078, 0.093]	[0.010, 0.300]
$corr_{v_1,v_2}$	correlation of male and female wage shocks	0.065	[0.014,0.121]	[-0.300, 0.500]
$\sigma^2_{F_{1,1}}$	variance of male initial wage (persistent)	0.183	[0.159, 0.209]	[0.010, 0.500]
$\sigma^2_{F_{2,1}}$	variance of female initial wage (persistent)	0.205	[0.175, 0.233]	[0.010, 0.500]
$corr_{F_{1,1},F_{2,1}}$	correlation of male and female initial wage (persistent)	0.250	[0.162,0.343]	[-0.300, 0.700]
$\sigma^2_{\alpha_1}$	variance of male initial wage (permanent)	0.076	[0.064, 0.089]	[0.010, 0.300]
$\sigma^2_{\alpha_2}$	variance of female initial wage (permanent)	0.060	[0.050, 0.071]	[0.010, 0.300]
$corr_{\alpha_1,\alpha_2}$	correlation of male and female initial wage (permanent)	0.409	[0.315,0.493]	[-0.300, 0.700]

Notes: "Persistent" and "permanent" in parentheses refer to the persistent and permanent components of log initial wage.

4.4 Goodness of Model Fit

How well does the model fit the data? Table 3 reports a group of first-order moments of household variables from the data, along with their counterparts implied by the model. The moments include average net worth of households, average male and female earnings and hours worked, and female non-participation rate. It is worth mentioning that the first-order moments are employed jointly with the second-order moments to estimate the preference parameters, and we have a heavily overidentified system. Therefore, the first-order moments are not matched mechanically. Nevertheless, for all moments the model fits the data well.

Figure 2 plots the life-cycle profiles of household endogenous variables, namely household consumption, asset, and hours worked, for both the model (blue solid lines) and the data (red dotted lines with shaded 95% confidence intervals). Although not targeted in calibration or estimation, the model still matches these life-cycle profiles reasonably well. Consumption in the model rises over the life cycle since wage risk, and the associated precautionary saving, as well as a fairly high de-

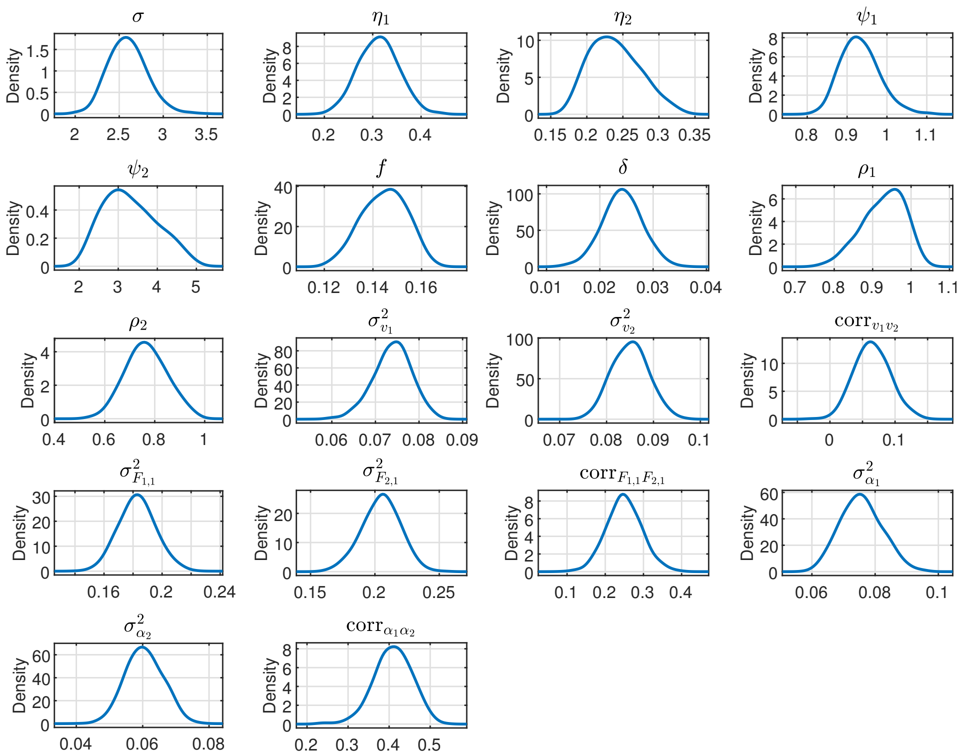

Figure 1: Distributions of Preference and Wage Parameters

Notes: This figure plots the marginal probability density functions of preference and wage parameters implied by the joint posterior distribution.

Table 3: Data vs. Model: First Moments

Moment	Description	Data	Model
$\mathbb{E}[A_t]$	average net worth	0.884	0.911
$\mathbb{E}[Y_{1,t}]$	average male earnings	1	0.965
$\mathbb{E}[Y_{2,t} \| H_{2,t} > 0]$	average female earnings | work	0.481	0.480
$\mathbb{E}[H_{1,t}]$	average male hours	1	0.999
$\mathbb{E}[H_{2,t} \| H_{2,t} > 0]$	average female hours | work	0.706	0.729
$\mathbb{E}[\mathbf{I}(H_{2,t} = 0)]$	female non-participation rate	0.154	0.160

Notes: "Model" results are the mean of each moment implied by the model and the posterior distribution of parameters.

gree of patience lead to low consumption early in life and subsequent positive consumption growth. Asset rises over the life cycle as households accumulate wealth to fund retirement consumption, but also for precautionary reasons to hedge against stochastic wage fluctuations. Lower average female hours originate both from lower hours conditional on working, but also from a significant non-participation rate. The model captures well the growth of consumption and asset over the life cycle in the data, as well as the stable male and female hours.

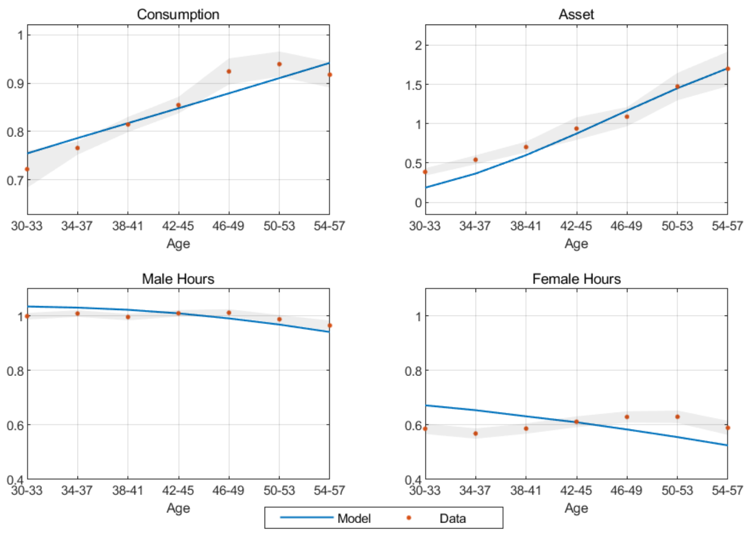

Figure 2: Data vs. Model: Life Cycles

Notes: This figure shows the life cycles of cross-sectional means in the model with parameters equal to the posterior means (blue solid lines) and in the data (red dotted lines) together with the 95% confidence interval (grey bands). Since the data do not include all types of consumption expenditures, the consumption life cycle from the data is scaled up to match the average consumption in the model. For ease of comparison, male and female hours are placed on the same scale.

Figure 3 shows the performance of the model in matching the second-order moments of wage, consumption, and earnings growth in the data, as well as those of the initial wage components. The model does an excellent job in predicting moments of the joint distribution of male and female wage growth (left panel), suggesting that the AR(1) specification provides a good approximation to the actual wage process in the data. Additionally, the model also closely captures the pattern of initial wage inequality (mid-left panels), an important source of inequality as highlighted by Huggett et al. (2011).

Beyond wages, the model is also able to replicate key features of consumption and earnings dynamics. It matches well the volatility of consumption and earnings growth (top mid-right panel). The minor discrepancies in the variances of consumption and female earnings growth are driven by the conflict between their variances

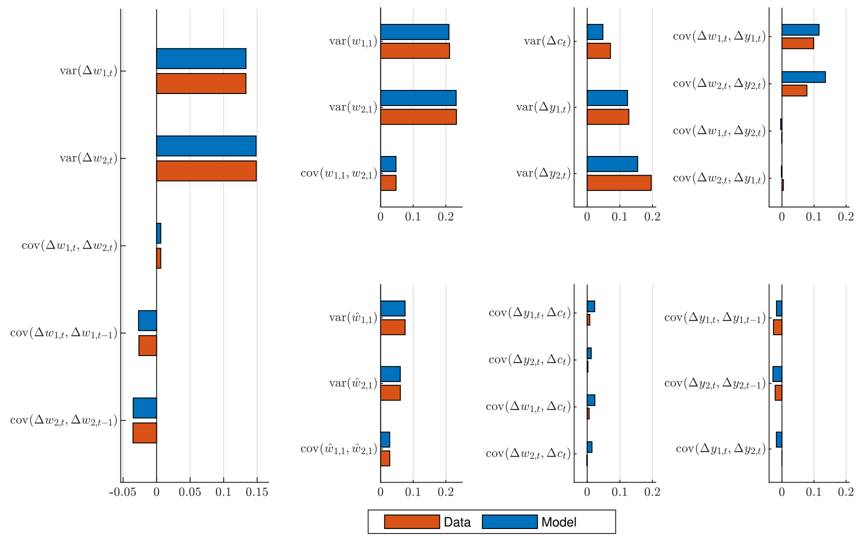

Figure 3: Data vs. Model: Second Moments

Notes: This figure shows the second moments of wage, consumption, and earnings growth in the model and in the data, together with those of the persistent and permanet initial wage components. "Model" results are the mean of each moment implied by the model and the posterior distribution of parameters. For ease of comparison, the mid-right and right panels are plotted on the same scale, and the same applies to the mid-left panels.

and covariances in the data. Specifically, the covariances between consumption and earnings/wages are fairly small in the data (bottom mid-right panel), which suggests that consumption is not affected much by wage shocks and therefore should not be too volatile. This, however, contradicts the large variance of consumption growth in the top mid-right panel. Since the model tries to match these moments simultaneously, it undershoots the variance and overpredicts the covariances. A similar case can be made for female earnings (top right panel vs. top mid-right panel).

Finally, in the bottom right panel we plot lagged auto- and cross-covariances of male and female earnings. Consistent with the data, male and female earnings growth in the model have negative autocorrelations, and their contemporaneous covariance is close to zero.

Overall, the evidences above suggest that our life-cycle model fits the data well, albeit not perfectly, and hence it is suitable for a quantitative examination of parameter uncertainty's effects on income tax policy.

5 Tax Policy Implications of Uncertainty

In this section, we study quantitatively the income tax policy implications of policymakers' uncertainty about household preferences and wage process, based on the life-cycle model in Section 3 and the empirical posterior distribution in Section 4. We first investigate how the uncertainty about preference and wage parameters affects the optimal design of income tax code. We then assess the welfare cost of this uncertainty by comparing the ex ante optimum to the scenario with perfect information about parameters. Finally, we perform sensitivity analysis regarding assumptions about government spending and budget constraint. Appendix B.1 further highlights the importance of accurately measuring the posterior distribution, while Appendix B.2 explores implications of alternative risk preferences of policymakers.[25]

5.1 Uncertainty and Optimal Tax Policy

5.1.1 Uncertainty's Effect on Optimal Tax Policy

To quantify the effects of uncertainty about household preferences and wage process on the optimal design of tax policy, we solve numerically two versions of the optimal tax policy problem described in Section 3.3. In one version, policymakers ignore the uncertainty and treat the point estimates (i.e., posterior means) of parameters $\bar{\Theta}$ as their true values when searching for the optimal tax policy. This is equivalent to using a degenerate posterior distribution with $\Pr(\Theta = \bar{\Theta}) = 1$ in the optimal tax policy problem. In the other version, policymakers take into account the uncertainty correctly in the policymaking process by using the true posterior distribution estimated from the data in Section 4.3. The difference in optimal tax policy between the two versions then reveals how tax policy should adjust in response to the existence of such uncertainty.

To ensure that our quantitative findings are pertinent to practical policy considerations, we calibrate the Pareto weights $\omega(\mathbf{s})$ in the social welfare function (6) and the taste for public consumption γ in (7) such that the status quo policy is optimal

[25] All quantitative results are based on model-simulated panels of 50,000 households over their life cycles. Further details about the computation method are in Appendix C.3.

based on the point estimates of parameters. Therefore, policymakers would have no incentive to deviate from the status quo policy except their concerns about parameter uncertainty. Such calibration strategy also serves as a reduced-form way of controlling for the effects of other economic and non-economic determinants of tax policy that are not modeled explicitly in our framework. Hence our quantitative analysis shall be understood as investigating the tax policy implications of uncertainty about household preferences and wage process, while holding constant the effects of other factors.

In particular, similar to Chang et al. (2018), Heathcote and Tsujiyama (2021), and Wu (2021), the Pareto weight function takes the following functional form:

$$\omega(\mathbf{s}) = \frac{\exp\left[\xi R(\alpha_1)\right]}{\int_{\mathbf{s}} \exp\left[\xi R(\alpha_1)\right] d\Phi_1(\mathbf{s})},$$

where $R(\alpha_1)$ is the percentile rank of male permanent wage component,[26] and ξ is a parameter that controls policymakers' "taste for redistribution": when $\xi = 0$, policymakers are utilitarian; a larger ξ implies that the policymakers value the welfare of high-wage households more, and thus a less progressive tax system is preferred. On the other hand, a larger γ indicates greater benefits from public consumption, which leads to a higher level of optimal income tax.

We also need to assign a value for σ_G in (7) that controls the curvature of utility function for public consumption. Given the lack of direct evidence on σ_G, we set it to 2.60, the posterior mean of its counterpart for private consumption σ, in our benchmark analysis. Sensitivity analysis regarding this choice is provided in Section 5.3. The values of ξ and γ that rationalize the status quo policy are 6.55 and 4.78, respectively.

The optimal tax policies based on the point estimates and the true posterior distribution are reported in Table 4. By construction, the optimal policy based on the point estimates are exactly the same as the status quo policy reported in Table 1. Taking into account the uncertainty about preference and wage parameters as represented by the posterior distribution, however, leads to a more progressive optimal tax policy, with an increase in progressivity by 0.021 (0.148 vs. 0.128). The level of

[26] We choose $R(\alpha_1)$ such that the Pareto weights are not affected by parameter uncertainty.

Table 4: Optimal Tax Policy

	Progressivity (τ)	Level (λ)
Based on Point Estimates	0.128	0.126
Based on Posterior Distribution	0.148	0.119

Notes: By construction, the optimal policy based on point estimates are the same as the status quo policy.

the optimal tax policy also falls by 0.007 (0.119 vs. 0.126). To get a better sense of what these differences imply about the income tax rates, Figure 4 plots the changes in marginal tax rates faced by households of various income levels. For households near the top of the income distribution (the right limit of the horizontal axes), their marginal tax rates would rise by about 3.0 percentage points. For households near the bottom of the income distribution (the left limit of the horizontal axes), their marginal tax rates would fall by about 2.5 percentage points. Hence, accounting for the uncertainty would raise the gap in marginal tax rate between the high- and low-income households by about 5.5 percentage points.

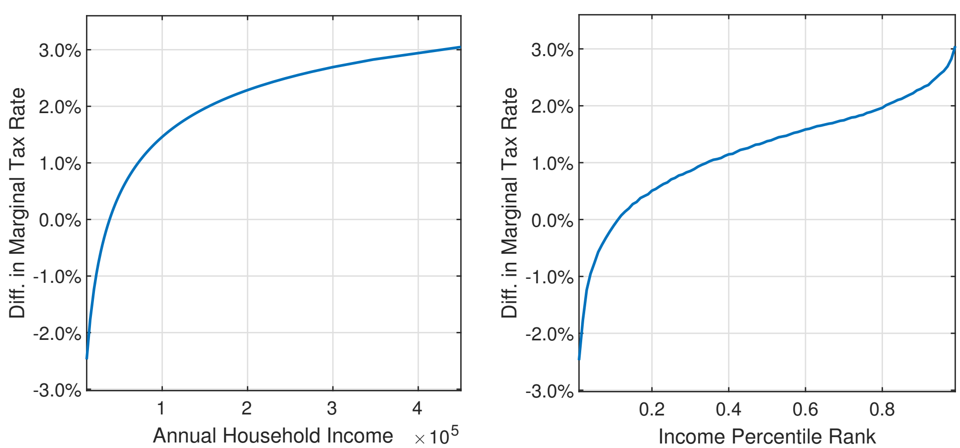

Figure 4: Uncertainty's Effect on Marginal Tax Rate

Notes: This figure plots the change in the optimal income tax scheculde (i.e., marginal tax rate) after accounting for the uncertainty about preference and wage parameters represented by the posterior distribution. The left panel is against household income in 2016 dollars, and the right panel is against the percentile rank of household income. The lower and upper limits of the horizontal axes correspond to the bottom and top 1% cutoff levels of the income distribution for married households.

5.1.2 Why More Progressive Optimal Tax?

Our theoretical analysis in Section 2 suggests that the effect of parameter uncertainty on optimal tax policy depends on how the choice of tax policy influences the shape of the welfare function with respect to the uncertain parameters. For example, if increasing tax progressivity makes the welfare function more convex with respect to these parameters, the optimal policy accounting for parameter uncertainty will be more progressive than the one that ignores it. This insight remains valuable for interpreting the quantitative findings in Table 4.

The left panel of Figure 5 plots the expected welfare gain from tax reform based on the entire posterior distribution (blue solid line) and the welfare gain based on the posterior means (red dashed line) as functions of tax progressivity. Both curves are hump-shaped, reflecting the trade-off between the benefit of public insurance through progressive taxation and the efficiency cost from labor distortions. The gap between the expected welfare gain and the welfare gain based on the posterior means corresponds to the impact of parameter uncertainty. As shown in the right panel of Figure 5, this gap widens with greater tax progressivity, hence the presence of parameter uncertainty favors a more progressive income tax.

The right panel of Figure 5 indicates that the overall "convexity" of the welfare gain function with respect to the uncertain parameters is amplified by tax progressivity.[27] However, because there are multiple uncertain parameters, the impact of tax progressivity on the shape of the welfare gain function may not be uniform across all dimensions. Figure 6 provides a closer look at how tax progressivity alters the welfare gain function with respect to three representative parameters. By construction, welfare gain is zero under the status quo policy, and the welfare gain function is flat (red dashed lines). As tax progressivity increases, however, the welfare gain function becomes convex in male wage persistence ρ_1, almost linear in male labor elasticity η_1, and concave in household risk aversion σ (blue solid lines). Therefore,

[27] Specifically, the difference is given by

$$\underbrace{\mathbb{E}_\Theta[W(\tau,\lambda,\Theta)]}_{\text{based on posterior distribution}} - \underbrace{W(\tau,\lambda,\mathbb{E}_\Theta[\Theta])}_{\text{based on point estimates}}.$$

For a fixed posterior distribution of Θ, the more convex is $W(\tau,\lambda,\cdot)$, the larger is the difference.

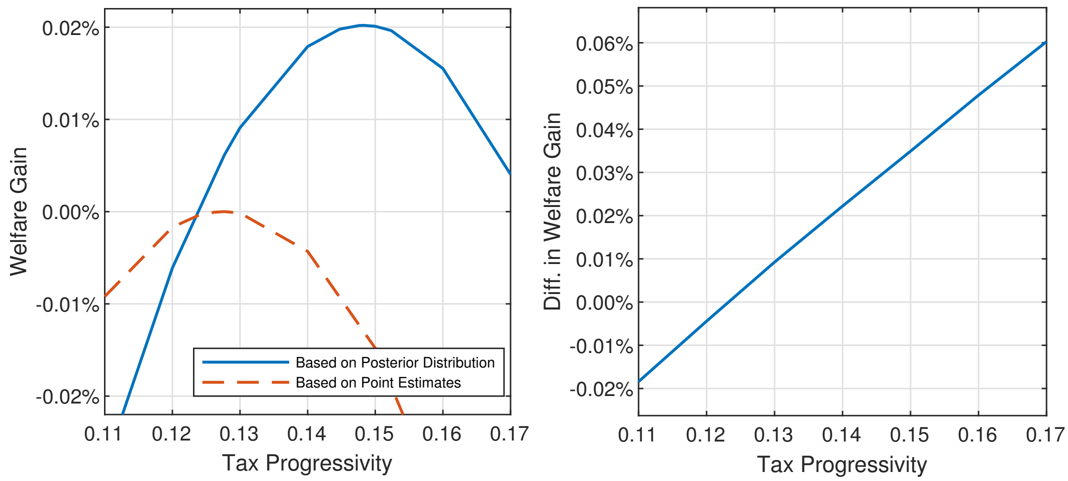

Figure 5: Tax Progressivity and Welfare

Notes: The left panel shows how the welfare gain relative to the status quo depends on the tax progressivity, based on the posterior distribution (blue solid line) and the point estimates (red dashed line). The right panel plots the difference in welfare gain between the two curves in the left panel. Welfare gain is reported as a percentage of lifetime consumption under the status quo tax policy and the point estimates of parameters.

uncertainty about each of these parameters *alone* contributes positively, neutrally, or negatively to optimal tax progressivity. Conclusions become less straightforward when accounting for interactions and correlations between uncertain parameters. For example, while the welfare gain appears almost linear in male labor elasticity in the center panel, this linearity may break down when other parameters assume different values. Curvature may also arise along directions of correlation with other parameters.[28]

In short, the more progressive optimal tax policy in the presence of parameter uncertainty is a quantitative outcome driven by the combined effects of uncertainty across all parameters. There is no universal answer to how parameter uncertainty affects tax policy, and as demonstrated in Appendix B.1, the correlations between uncertain parameters and the shape of their distributions are all important factors. Therefore, careful, case-specific quantitative analyses are essential for addressing

[28] A simple example is $f(x, y) = xy$. Although the function is linear in both x and y individually, if x and y are perfectly positively correlated, $f(x, y)$ is similar to x^2 and convex. Conversely, if x and y are perfectly negatively correlated, $f(x, y)$ is similar to $-x^2$ and concave. This highlights the crucial role of parameter correlations in analyses involving parameter uncertainty.

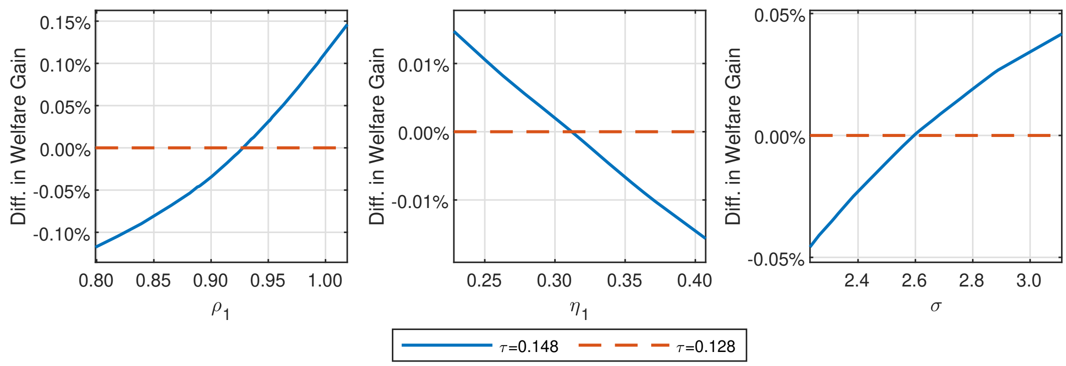

Figure 6: Welfare Gain and Uncertain Parameters

Notes: This figure plots the welfare gain function against the male wage persistence ρ_1 (left panel), male labor elasticitiy η_1 (center panel), and household risk aversion σ (right panel), when tax progressivity is increased from the status quo (red dashed line) to the optimal one based on the posterior distribution in Table 4 (blue solid line). In each plot, the other parameters are set at their point estimates, and the welfare gain at the point estimates is normalized to zero.

such questions.

5.1.3 Which Uncertainty is More Important?

To understand the importance of uncertainty about each aspect of the economy to the optimal design of tax policy, we conduct decomposition exercises based on our quantitative model. To keep the decomposition results informative and transparent, we categorize the uncertain parameters in two ways: i) those related to household preferences and those governing the idiosyncratic wage process; ii) male-related, female-related, and gender-neutral.[29]

The first column ("ΔProgressivity") of Table 5 reports the contribution of uncertainty about each parameter group to the change in optimal tax progressivity. Our results indicate that the increase in optimal tax progressivity reported in Table 4 is primarily driven by uncertainty about the idiosyncratic wage process (113%), while the effect of uncertainty about household preferences is smaller and in the opposite direction (-9%). The interaction between uncertainties about wage and preference parameters contributes negatively to optimal tax progressivity, but its

[29]For example, the male (female) labor supply elasticity η_1 (η_2) and wage persistence ρ_1 (ρ_2) are in the male (female) group, whereas the time discount rate δ and the correlation between male and female wage shocks $corr_{v_1,v_2}$ are considered gender-neutral.

Table 5: Decomposition: Uncertainty and Tax Progressivity

	ΔProgressivity (1)	Uncertainty (2)	Sensitivity (1)/(2)
Overall	100%	100%	1
A. Preferences vs. Wage Process			
Preference	−9%	26%	−0.34
Wage	113%	100%	1.13
Interaction	−4%	−26%	0.17
B. Male vs. Female			
Male	85%	97%	0.88
Female	34%	40%	0.87
Neutral	−5%	25%	−0.20
Interaction	−14%	−62%	0.23

Notes: "ΔProgressivity" denotes the change in (ex ante) optimal tax progressivity due to parameter uncertainty. "Uncertainty" is measured by the standard deviation of ex post optimal tax progressivity induced by parameter uncertainty. "Interaction" refers to the effects due to the coexistence of uncertainty about different groups of parameters. The results are normalized such that the total contribution equals 100%.

effect is quantitatively small (−4%).[30] On the other hand, uncertainty about male-related parameters explains 85% of the change in optimal tax progressivity, and the contributions of uncertainties about female-related and gender-neutral parameters are 34% and −5%, respectively. The interaction effect remains negative but is somewhat larger in this case, accounting for −14% of the total effect.

However, the results in the first column may not tell the full story since a larger effect of uncertainty about one group of parameters on optimal policy could stem from either i) there is a lot of uncertainty about these parameters, or ii) the optimal policy is more sensitive to uncertainty about these parameters. To separate these two channels, we need to first introduce a universal measure of uncertainty that is comparable across parameters with distinct economic interpretations. Given our focus on optimal tax progressivity, we choose to measure uncertainty by the standard deviation of *ex post* optimal tax progressivity induced by uncertainty about each group of parameters. More specifically, the ex post optimal tax policy is the opti-

[30] The interaction effect is calculated as the total effect from uncertainty about all parameters minus the sum of the individual effects from each parameter group alone.

mal policy after parameter uncertainty is resolved, which is a function of parameter Θ and given by

$$\left(\widetilde{\tau}^*(\Theta), \widetilde{\lambda}^*(\Theta)\right) = \arg\max_{(\tau,\lambda)} W(\tau, \lambda, \Theta).$$

Intuitively, if uncertainty about a parameter does not lead to significant variations in the ex post optimal policy, then no matter how dispersed is the posterior distribution of this parameter, there is not much uncertainty for policymakers about which policy to choose.

The second column ("Uncertainty") of Table 5 reports the decomposition of uncertainty based on this measure. While the effect of uncertainty about wage process on optimal tax progressivity is more than twelve times the effect of uncertainty about household preferences (113% vs. –9%) , uncertainty about wage process is only about four times the uncertainty about household preferences (100% vs. 26%).[31] This suggests that optimal tax progressivity is more sensitive to uncertainty about wage process than household preferences. More specifically, the third column ("Sensitivity") simply computes the ratio of the first column to the second column, and the results show that the optimal tax progressivity is three times as sensitive to uncertainty about wage process (1.13 vs. –0.34). Therefore, uncertainty about wage process explains most of the change in optimal tax progresssivity not only because there is more uncertainty, but also because the optimal policy is more sensitive to it. On the other hand, while uncertainty about male-related parameters accounts for the majority of the change in optimal tax progressivity, the optimal policy is about equally sensitive to uncertainty about male- and female-related parameters.

5.2 Welfare Cost of Uncertainty

When policymakers are uncertain about the true values of key economic parameters, the ex ante optimal policy based on the posterior distribution in Section

[31] The smaller uncertainty about preference parameters primarily arises from the additional structural assumptions required for their estimation. While wage parameters are estimated based solely on the statistical model of the wage process, preference parameters rely on the full life-cycle model, incorporating all modeling assumptions, including those related to the wage process. These extra assumptions help pin down the parameters, leading to tighter posterior distributions for preference parameters.

5.1 is in general not optimal ex post. This leads to welfare losses compared to the "first-best" scenario in which policymakers have perfect information about parameters and can set the tax policy contingent on the parameter values. We refer to such losses as the welfare cost of uncertainty since they can be eliminated by a signal that reveals the true values of parameters to the policymakers. It is useful to get a sense of how large this welfare cost is since there are potential ways of improving our knowledge about these parameters, yet at various degrees of costs. If the welfare cost of parameter uncertainty turns out to be smaller than the cost of eliminating such uncertainty, it would be rational for the policymakers to remain ignorant. If the opposite is true, more resources should be devoted to activities that can help us achieve better estimates of these parameters.

To quantify the welfare cost of uncertainty, let us first define the first-best tax policy which is a parameter-contingent policy plan that implements the ex post optimal tax policy state-by-state:[32]

$$(\widetilde{\tau}^*(\Theta), \widetilde{\lambda}^*(\Theta)) = \arg\max_{(\tau,\lambda)} W(\tau, \lambda, \Theta),$$

where $W(\tau, \lambda, \Theta)$ is the same as in Section 5.1, and it represents the welfare gain from a tax reform relative to the status quo. The first-best tax policy maximizes the welfare for each parameter state, and hence it is the best the policymakers can do with perfect information about parameters. The welfare loss from adopting a parameter-invariant tax policy (τ, λ) relative to the first-best is then

$$\widehat{W}(\tau, \lambda, \Theta) \equiv W(\widetilde{\tau}^*(\Theta), \widetilde{\lambda}^*(\Theta), \Theta) - W(\tau, \lambda, \Theta). \tag{10}$$

Notice that the welfare loss $\widehat{W}(\tau, \lambda, \Theta)$ depends on the true parameter state Θ, and it is always nonnegative since no policy can induce higher welfare than the first-best policy.

The implementation of the first-best policy requires exact knowledge about the parameters, and hence it is infeasible when policymakers face parameter uncertainty. The best the policymakers can do in this case is to choose a parameter-

[32]Here "state" refers to the state of nature that determines the values of parameters.

invariant tax policy to minimize the welfare loss relative to the first-best. This gives rise to the following optimal tax policy problem:

$$(\tau^*, \lambda^*) = \arg\min_{(\tau,\lambda)} \Gamma^{-1} \left(\int_{\Theta} \Gamma \left(\widehat{W}(\tau, \lambda, \Theta) \right) d\Pi(\Theta) \right), \tag{11}$$

where $\Gamma(\cdot)$ is again a strictly increasing function reflecting the risk preferences of policymakers, and $\Pi(\Theta)$ is the posterior distribution of parameters. For now, we maintain our previous assumption that policymakers are risk-neutral, i.e., $\Gamma(\cdot)$ is linear. And under this assumption, it is easy to verify that this problem of minimizing the welfare loss relative to the first-best is equivalent to the problem of maximizing the welfare gain relative to the status quo in Section 5.1. As a result, the ex ante optimal tax policy based on the posterior distribution is the same as in Table 4, i.e., $\tau^* = 0.148$, $\lambda^* = 0.119$.

The left panel of Figure 7 plots the distribution of the ex post optimal tax progressivity implied by the posterior distribution of parameters. Depending on the parameter state, the ex post optimal tax progressivity varies considerably. However, since policymakers are uncertain about the true values of parameters, the ex ante optimal tax progressivity is fixed at $\tau^* = 0.148$, which leads to ex post welfare losses relative to the first-best outcome. The right panel of Figure 7 shows the distribution of this welfare loss, which is right-skewed with a lower bound of zero. The expected welfare loss is equivalent to 0.38% of lifetime consumption, which is about 55 billion dollars per year based on the 2019 U.S. consumption data.

It is worth stressing that the welfare cost of uncertainty we report only captures its distortionary effects on income tax policy. Since there are other government policy decisions that rely on information about household preferences and wage process, the total welfare cost of uncertainty through distortions to all policy decisions is likely much larger. Our finding thus indicates substantial potential welfare gains from activities that improve our knowledge about these aspects of the economy.

5.3 Alternative Assumptions about Government Spending

Under parameter uncertainty, there is generally no parameter-invariant tax policy that can consistently balance the government budget with a fixed level of spend-

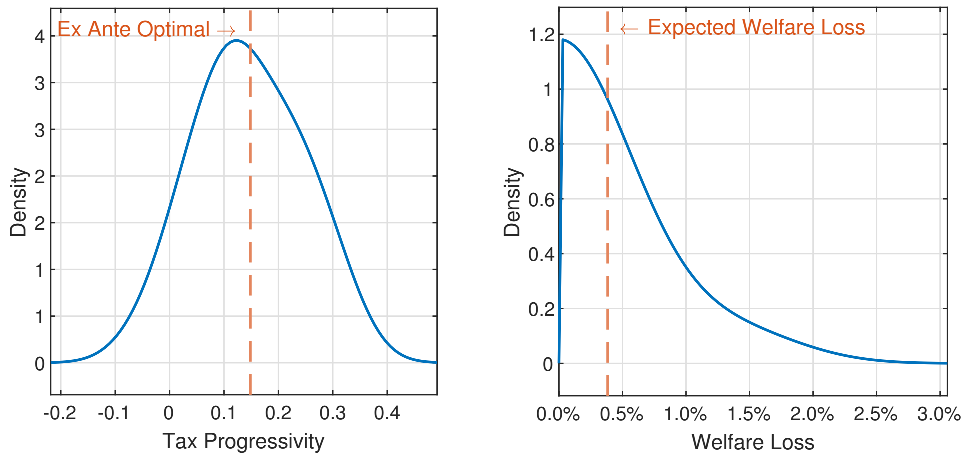

Figure 7: Distributions of the Ex Post Optimal Policy and Welfare Loss from Uncertainty

Notes: This figure shows the distributions of the ex post optimal tax progressivity (left panel) and the welfare loss relative to the first-best under the ex ante optimal tax policy (right panel). Welfare loss is reported as a percentage of lifetime consumption under the status quo tax policy and the point estimates of parameters.

ing. Therefore, in our benchmark analysis in Section 5.1, which quantifies the effect of parameter uncertainty on optimal tax policy, we assumed endogenous government spending on public consumption, incorporated into household lifetime utility as shown in (7). In this section, we conduct sensitivity analysis to explore alternative assumptions about government spending and budget constraint.

First, a key parameter related to public consumption is σ_G, which determines how quickly the marginal utility of public consumption declines as its level increases. Direct evidence for its value is limited. In our benchmark analysis, we set $\sigma_G = 2.6$, based on the posterior mean of σ, its counterpart for private consumption. Panel A of Table 6 reports findings from our sensitivity analysis regarding σ_G.[33] When $\sigma_G = 1$, implying log utility for public consumption as in Heathcote et al. (2017), the effect of parameter uncertainty on optimal tax progressivity increases from 0.021 to 0.027. Conversely, when $\sigma_G = 4$, the effect remains positive but decreases slightly to 0.015.

Second, while it is infeasible to impose a balanced government budget across all

[33]Note that γ is not a free parameter, and it is endogenously calibrated together with ξ in Pareto weights such that the status quo tax policy is optimal when parameter uncertainty is ignored. For each value of σ_G, γ and ξ are recalibrated as in the benchmark analysis.

Table 6: Alternative Assumptions about Government Spending

	ΔProgressivity	ΔLevel
A. Endogenous Government Spending		
$\sigma_G = 2.6$ (Benchmark)	0.021	-0.007
$\sigma_G = 1$	0.027	-0.007
$\sigma_G = 4$	0.015	-0.006
B. Exogenous Government Spending		
$\mathbb{E}\{G\} = \bar{G}$	0.028	-0.006

Notes: This table reports the effects of parameter uncertainty on optimal tax poilcy under alternative assumptions about government spending.

possible parameter states with a fixed level of government spending, we can instead impose a balanced budget *in expectation*:

$$\int_{\Theta} \mathrm{Tax}(\tau, \lambda, \Theta) d\Pi(\Theta) = \bar{G},$$

where $\mathrm{Tax}(\tau, \lambda, \Theta)$ represents government tax revenue under policy (τ, λ) and parameter state Θ, and $\bar{G}$ denotes the fixed level of government spending.[34] Under this specification, we assume *wasteful* government spending and exclude public consumption from household utility. Panel B of Table 6 shows that imposing such budget constraint increases the effect of parameter uncertainty on optimal tax progressivity, amplifying the change from 0.021 to 0.028.

Overall, the sensitivity analysis suggests that our findings about the effect of parameter uncertainty on optimal tax policy are qualitatively and, to some extent, quantitatively robust to changes in assumptions about government spending and budget constraint.

6 Conclusions

This study underscores the critical role of parameter uncertainty in shaping optimal income tax policy. We introduce a novel framework that explicitly incorporates

[34]The value of $\bar{G}$ is set to the government tax revenue under the status quo policy at the posterior means of parameters such that, consistent with our benchmark analysis, the status quo policy is optimal when parameter uncertainty is ignored.

parameter uncertainty into policy decision-making. Through theoretical insights and quantitative analysis using a dynamic life-cycle model, we demonstrate that accounting for uncertainty about household preferences and wage processes significantly influences the optimal level of tax progressivity.

Our findings indicate that uncertainty about preference and wage parameters leads to a more progressive optimal income tax, with a 5.5 percentage-point increase in the marginal tax rate gap between high- and low-income households. Wage parameter uncertainty, in particular, has the most substantial impact, highlighting the need to better understand wage dynamics. The posterior distribution plays a key role by encapsulating critical information about correlations and the shape of parameter distributions.

By bridging gaps in the existing literature, this study offers a framework for incorporating uncertainty into policy design and opens doors for broader applications of uncertainty quantification. The methodology we employ to measure uncertainty from data and analyze its policy implications is versatile and can be applied to other areas of the economy or government policies beyond income taxation.

Lastly, for computational reasons, we have assumed that policymakers are passive learners in the sense that they take the data they observe as given. It would be interesting to explore what would happen if active learning is introduced such that policymakers can take actions that directly or indirectly affect the information they receive, although such an extension may require substantial simplification of the model along other dimensions to be feasible.

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Online Appendix

When in Doubt, Tax More Progressively? Uncertainty and Progressive Income Taxation

Minsu Chang and Chunzan Wu

A Supplementary Theoretical Results

A.1 Welfare Gain from Tax Reform

In this section, we derive the closed-form formula for the welfare gain from tax reform $W(\tau, \Theta)$ of Section 2.2 in greater detail. Given the income tax function, maximizing household utility subject to the budget constraint yields the optimal household labor supply

$$H(z; \tau, \lambda, \Theta) = (1-\tau)^{\frac{1}{1+\eta^{-1}}}.$$

Note that household labor supply does not depend on productivity z or tax level λ, and households treat public consumption G as exogenous when making labor supply decisions. Private consumption of productivity z household is then simply the after-tax income

$$C(z; \tau, \lambda, \Theta) = (1-\lambda)[zH(z; \tau, \lambda, \Theta)]^{1-\tau}.$$

Based on the government budget constraint, we can express government spending on public consumption as

$$\begin{aligned} G(\tau, \lambda, \Theta) =& \int_z zH(z; \tau, \lambda, \Theta) dF_z(z) - (1-\lambda) \int_z [zH(z; \tau, \lambda, \Theta)]^{1-\tau} dF_z(z) \\ =& (1-\tau)^{\frac{1}{1+\eta^{-1}}} - (1-\lambda)(1-\tau)^{\frac{1-\tau}{1+\eta^{-1}}} \underbrace{\int_z z^{1-\tau} dF_z(z)}_{=\mathbb{E}[z^{1-\tau}]}. \end{aligned}$$

Suppose that the policymakers are utilitarian. The social welfare under parameter $\Theta = (\eta, \sigma_z)$ is simply

$$\text{SWF}(\tau, \lambda, \Theta) = \int_z \left[\ln C(z; \tau, \lambda, \Theta) - \frac{H(z; \tau, \lambda, \Theta)^{1+\eta^{-1}}}{1+\eta^{-1}} + \gamma \ln G(\tau, \lambda, \Theta) \right] dF_z(z).$$

Plugging in the consumption and labor supply policy functions and integrating over the distribution of household productivity, we have

$$\text{SWF}(\tau, \lambda, \Theta) = \ln(1-\lambda) - \frac{(1-\tau)}{2}\sigma_z^2 + \frac{1-\tau}{1+\eta^{-1}} \ln(1-\tau) - \frac{1-\tau}{1+\eta^{-1}} + \gamma \ln G(\tau, \lambda, \Theta).$$

For tractability, we assume that tax level λ is set contingent on tax progressivity τ and parameter Θ to maximize the ex post social welfare. The ex post optimality condition for λ is then

$$\frac{1}{1-\lambda} = \frac{\gamma}{G(\tau, \lambda, \Theta)} \frac{\partial G(\tau, \lambda, \Theta)}{\partial \lambda},$$

which implies that the ex post optimal tax level is

$$\lambda^*(\tau, \Theta) = 1 - \frac{(1-\tau)^{\frac{\tau}{1+\eta^{-1}}}}{(1+\gamma)\mathbb{E}[z^{1-\tau}]} = 1 - \frac{(1-\tau)^{\frac{\tau}{1+\eta^{-1}}}}{(1+\gamma)} e^{\frac{\tau(1-\tau)\sigma_z^2}{2}}.$$

Note that when $\tau = 0$, the ex post optimal tax level is always $\lambda = \frac{\gamma}{1+\gamma}$, independent of parameter Θ. The ex post optimal amount of public consumption is then

$$G(\tau, \lambda^*(\tau, \Theta), \Theta) = \frac{\gamma}{1+\gamma}(1-\tau)^{\frac{1}{1+\eta^{-1}}}.$$

Let $(\tau_{sq}, \lambda_{sq})$ denote the status quo tax policy. If policymakers adopt a new tax policy with progressivity τ and the corresponding ex post optimal tax level $\lambda^*(\tau, \Theta)$, the social welfare gain from such tax reform is then

$$\Delta(\tau, \Theta) \equiv \text{SWF}(\tau, \lambda^*(\tau, \Theta), \Theta) - \text{SWF}(\tau_{sq}, \lambda_{sq}, \Theta).$$

When $\tau_{sq} = 0$ and $\lambda_{sq} = \frac{\gamma}{1+\gamma}$, we have

$$\Delta(\tau, \Theta) = \frac{1}{2}\sigma_z^2 \tau(2-\tau) + \frac{1}{1+\eta^{-1}} \left[(1+\gamma)\ln(1-\tau) + \tau \right].$$

To convert the welfare gain $\Delta(\tau, \Theta)$ into consumption equivalent variation $W(\tau, \Theta)$, we first need to find the percentage change in consumption x that would generate the same welfare change as the tax reform, i.e.,

$$\Delta(\tau, \Theta) = \int_z [\ln((1+x)C(z; \tau_{sq}, \lambda_{sq}, \Theta)) - \ln C(z; \tau_{sq}, \lambda_{sq}, \Theta)] \, dF_z(z) = \ln(1+x),$$

which implies

$$x = e^{\Delta(\tau,\Theta)} - 1.$$

Hence the total amount of consumption transfers is

$$W(\tau, \Theta) = x \int_z C(z; \tau_{sq}, \lambda_{sq}, \Theta) dF_z(z) = \left(e^{\Delta(\tau,\Theta)} - 1\right) \frac{1}{1+\gamma}.$$

A.2 Signs of Derivatives

For the static model in Section 2.2, we have the following derivatives of $\Delta(\tau, \Theta)$ with respect to the Frisch elasticity η:

$$\begin{aligned}
\Delta_\eta &= \eta^{-2}(1+\eta^{-1})^{-2} \left[(1+\gamma)\ln(1-\tau) + \tau\right]; \\
\Delta_{\eta\eta} &= -2\eta^{-3}(1+\eta^{-1})^{-3} \left[(1+\gamma)\ln(1-\tau) + \tau\right]; \\
\Delta_{\eta\tau} &= \eta^{-2}(1+\eta^{-1})^{-2} \left(1 - \frac{1+\gamma}{1-\tau}\right); \\
\Delta_{\eta\eta\tau} &= -2\eta^{-3}(1+\eta^{-1})^{-3} \left(1 - \frac{1+\gamma}{1-\tau}\right).
\end{aligned}$$

Since $W(\tau, \Theta) = \left(e^{\Delta(\tau,\Theta)} - 1\right)/(1+\gamma)$, we have

$$W_{\eta\eta\tau} = \frac{1}{1+\gamma} \left\{ e^{\Delta} \left[\Delta_{\eta\eta\tau} + 2\Delta_\eta \Delta_{\eta\tau}\right] + e^{\Delta}\Delta_\tau \left[\Delta_{\eta\eta} + (\Delta_\eta)^2\right] \right\}.$$

Since $\bar{\tau}$ maximizes $W(\tau, \bar{\Theta})$ and thus $\Delta(\tau, \bar{\Theta})$ by definition, we have $\Delta_\tau(\bar{\tau}, \bar{\Theta}) = 0$. It follows that when $\bar{\tau} \in (0, 1)$ and $\gamma > 0$,

$$W_{\eta\eta\tau}(\bar{\tau}, \bar{\Theta}) = \frac{1}{1+\gamma} e^{\Delta(\bar{\tau},\bar{\Theta})} [\underbrace{\Delta_{\eta\eta\tau}(\bar{\tau}, \bar{\Theta})}_{>0} + 2 \underbrace{\Delta_\eta(\bar{\tau}, \bar{\Theta})}_{<0} \underbrace{\Delta_{\eta\tau}(\bar{\tau}, \bar{\Theta})}_{<0}] > 0.$$

Similarly, we have the following derivatives of $\Delta(\tau, \Theta)$ with respect to the magnitude of idiosyncratic productivity risk σ_z:

$$\begin{aligned}
\Delta_{\sigma_z} &= \sigma_z \tau(2-\tau), \\
\Delta_{\sigma_z\sigma_z} &= \tau(2-\tau), \\
\Delta_{\sigma_z\tau} &= 2\sigma_z(1-\tau), \\
\Delta_{\sigma_z\sigma_z\tau} &= 2(1-\tau),
\end{aligned}$$

and

$$W_{\sigma_z\sigma_z\tau} = \frac{1}{1+\gamma}\left\{e^{\Delta}[\Delta_{\sigma_z\sigma_z\tau} + 2\Delta_{\sigma_z}\Delta_{\sigma_z\tau}] + e^{\Delta}\Delta_\tau[\Delta_{\sigma_z\sigma_z} + (\Delta_{\sigma_z})^2]\right\}.$$

Notice again that $\Delta_\tau(\bar{\tau}, \bar{\Theta}) = 0$, and hence when $\bar{\tau} \in (0,1)$ and $\gamma > 0$,

$$W_{\sigma_z\sigma_z\tau}(\bar{\tau}, \bar{\Theta}) = \frac{1}{1+\gamma} e^{\Delta(\bar{\tau},\bar{\Theta})}[\underbrace{\Delta_{\sigma_z\sigma_z\tau}(\bar{\tau}, \bar{\Theta})}_{>0} + 2\underbrace{\Delta_{\sigma_z}(\bar{\tau}, \bar{\Theta})}_{>0}\underbrace{\Delta_{\sigma_z\tau}(\bar{\tau}, \bar{\Theta})}_{>0}] > 0.$$

A.3 Implications of Reparameterization for the Effect of Parameter Uncertainty

Consider the general setting in Section 2.1, where there is uncertainty about a model parameter θ. Suppose we reparameterize the model by defining $\theta = \Phi(x)$, where Φ is a monotonic function (e.g., $\theta = 1/x$), so that the model is now expressed in terms of x instead of θ. Let $P_\theta(\theta)$ denote the probability density function (pdf) for θ. The pdf for x is then given by

$$P_x(x) = P_\theta(\Phi(x))|\Phi'(x)|.$$

The expected welfare under policy τ with parameter x is

$$\int_x W(\tau, \Phi(x))P_x(x)dx = \int_x W(\tau, \Phi(x))P_\theta(\Phi(x))|\Phi'(x)|dx = \int_\theta W(\tau, \theta)P_\theta(\theta)d\theta.$$

Therefore, the expected welfare taking into account parameter uncertainty is invariant to reparameterization, as long as the posterior distribution of the parameter is adjusted appropriately, i.e., use P_x for x and P_θ for θ. An immediate implication of this equivalence is that the optimal policy taking into account parameter uncertainty,

$$\tau^* = \arg\max_\tau \int_x W(\tau, \Phi(x)) P_x(x) dx = \arg\max_\tau \int W(\tau, \theta) P_\theta(\theta) d\theta,$$

remains unchanged after reparameterization.

However, the reparameterization may affect the optimal policy when uncertainty is ignored. When the model is parameterized by θ, the optimal policy ignoring uncertainty, denoted $\bar{\tau}$, is given by:

$$\bar{\tau} = \arg\max_\tau W(\tau, \mathbb{E}(\theta)),$$

where $\mathbb{E}(\theta)$ is the expected value of θ, serving as a point estimate.

Under the reparameterization, the optimal policy ignoring uncertainty, denoted $\tilde{\tau}$, becomes:

$$\tilde{\tau} = \arg\max_\tau W(\tau, \Phi(\mathbb{E}(x))) = \arg\max_\tau W\left(\tau, \Phi(\mathbb{E}(\Phi^{-1}(\theta)))\right),$$

where $\mathbb{E}(x)$ is the expected value of x and the point estimate.

Unless Φ is linear, $\mathbb{E}(\theta)$ is generally not equal to $\Phi(\mathbb{E}(\Phi^{-1}(\theta)))$, so the policies $\bar{\tau}$ and $\tilde{\tau}$ may differ, i.e., $\bar{\tau} \neq \tilde{\tau}$. For instance, if we consider a reparameterization with $\theta = 1/x$, $\mathbb{E}(\theta)$ is generally not equal to $1/\mathbb{E}(1/\theta)$.

This difference may affect our evaluation of the effect of parameter uncertainty on optimal policy, which is defined as the discrepancy between the optimal policy accounting for uncertainty (τ^*) and the optimal policy ignoring uncertainty. Since $\bar{\tau}$ and $\tilde{\tau}$ differ, conclusions regarding the effect of parameter uncertainty may vary depending on the parameterization, even though the optimal policy accounting for uncertainty, τ^*, remains the same across reparameterizations. For instance, if we reparameterize the static model in Section 2.2 using the inverse of the labor elasticity, η^{-1}, we can no longer conclusively determine the sign of the effect of its uncertainty.

A.4 Exploration with Heathcote et al. (2017)'s Model

Heathcote et al. (2017) (hereafter HSV) develop a tractable model to study the optimal income tax problem with a closed-from expression for social welfare. In this section, we attempt to extend their model to include parameter uncertainty, and unfortunately, we find that it is generally difficult to obtain a closed-form expression for the expected welfare that is needed for analyses with parameter uncertainty. The main difficulty is that social welfare is highly nonlinear in the uncertain parameters, and integration of such nonlinear function for the expected welfare often does not allow a closed-from expression.

To make the point, it is enough to consider a stripped-down version of the HSV model. In particular, we shut down the endogenous skill investment and preference heterogeneity in their model, and keep their original notation for ease of comparison. The closed-form social welfare $\mathcal{W}(g,\tau)$ then becomes:[35]

$$\begin{aligned}\mathcal{W}(g,\tau) =& \log(1-g) + \chi \log g + (1+\chi)\frac{\log(1-\tau)}{(1+\hat{\sigma})(1-\tau)} - \frac{1}{1+\hat{\sigma}} \\ &- (1-\tau)^2 \frac{\upsilon_\omega}{2} \\ &+ (1+\chi)\left[\frac{1}{\hat{\sigma}}\upsilon_\epsilon - \sigma\frac{1}{\hat{\sigma}^2}\frac{\upsilon_\epsilon}{2}\right].\end{aligned}$$

Here g is the fraction of output devoted to public consumption, and τ is the degree of tax progressivity. $\hat{\sigma} = \frac{\sigma+\tau}{1-\tau}$ where $\frac{1}{\hat{\sigma}}$ and $\frac{1}{\sigma}$ are the tax-modified and unmodified labor elasticities, respectively. υ_ω is the cross-sectional variance of the uninsurable wage shocks α, and υ_ϵ is the variance of the insurable wage shocks ϵ. χ is the taste parameter for the public good G. The sum of the first four terms is the same as the social welfare from a representative agent model. The fifth term is associated with uninsurable shocks, and the remaining terms are related to insurable shocks.

When there is parameter uncertainty, as explained in our main text, we need to first convert welfare gains from tax reform into consumption equivalent variations

[35] The formula is based on Proposition 4 of Heathcote et al. (2017). When we abstract from endogenous skill investment and from preference heterogeneity, equation (30) in their paper can be simplified. Term (b), (c), (d) are associated with endogenous skill investment, and (e) is with preference heterogeneity. Furthermore, we assume $\gamma = \beta$ so that term (f) is approximated by $-(1-\tau)^2\frac{\upsilon_\omega}{2}$.

such that they can be meaningfully compared across parameter states. With log utility in consumption, the welfare gain of adopting policy (g, τ) in comparison to the baseline policy (g_0, τ_0) is, in consumption change,

$$[\exp(\mathcal{W}(g,\tau) - \mathcal{W}(g_0,\tau_0)) - 1]\, C(g_0,\tau_0),$$

where $C(g_0, \tau_0)$ is the total consumption under policy (g_0, τ_0).

From Corollary 6 of HSV, the welfare-maximizing g is given by $g = \frac{\chi}{1+\chi}$. Suppose there is no uncertainty in χ, then g can always be set at the welfare-maximizing level without the exact knowledge about other parameters. Hence, with some abuse of notation, we denote the social welfare as a function of τ hereafter, $\mathcal{W}(\tau)$. Let the status quo tax progressivity be $\tau_0 = 0$, and we have

$$\begin{aligned}
\exp(\mathcal{W}(\tau)) =&(1-g)\cdot g^{\chi}\cdot(1-\tau)^{\frac{(1+\chi)}{(1+\hat{\sigma})(1-\tau)}}\cdot\exp\left(-\frac{1}{1+\hat{\sigma}}\right)\\
&\times\exp\left(-(1-\tau)^2\frac{\upsilon_\omega}{2}\right)\cdot\exp\left((1+\chi)\left[\frac{1}{\hat{\sigma}}\upsilon_\epsilon-\sigma\frac{1}{\hat{\sigma}^2}\frac{\upsilon_\epsilon}{2}\right]\right)\\
\exp(\mathcal{W}(0)) =&(1-g)\cdot g^{\chi}\cdot\exp\left(-\frac{1}{1+\sigma}\right)\\
&\times\exp\left(-\frac{\upsilon_\omega}{2}\right)\cdot\exp\left((1+\chi)\frac{1}{\sigma}\frac{\upsilon_\epsilon}{2}\right)\\
\exp(\mathcal{W}(\tau)-\mathcal{W}(0)) =&(1-\tau)^{\frac{(1+\chi)}{(1+\sigma)}}\cdot\exp\left(\frac{\tau}{\sigma+1}\right)\\
&\times\exp\left((2-\tau)\tau\frac{\upsilon_\omega}{2}\right)\cdot\exp\left((1+\chi)\left[\frac{1}{\hat{\sigma}}-\frac{\sigma}{2\hat{\sigma}^2}-\frac{1}{2\sigma}\right]\upsilon_\epsilon\right)
\end{aligned}$$

The expected welfare gain is the integration of the welfare gain in consumption with respect to the posterior distribution of uncertain parameters (e.g., σ):

$$\mathbb{E}\left[\left(\exp(\mathcal{W}(\tau)-\mathcal{W}(0))-1\right)C(0)\right],$$

where $C(0) = \frac{1}{1+\chi}\exp\left(\frac{\upsilon_\epsilon}{2\sigma}\right)$, and we can already see that it is in general difficult to obtain a closed-form formula.[36]

[36]We can work out a case where a closed form of the expected welfare gain is available when υ_ω is the only uncertain parameter and its uncertainty can be characterized by a uniform distribution (available upon request). However, in general, getting a closed form for the integral of the welfare

B Additional Quantitative Analyses

In this section, we provide additional quantitative analyses complementary to those in Section 5.

B.1 The Posterior Distribution Matters

One advantage of our structural Bayesian approach of dealing with parameter uncertainty over the standard sensitivity analysis in the literature is that our posterior distribution estimated from the data contains information about the correlations between uncertain parameters and the shape of their distribution. Through counterfactual experiments, we demonstrate in Table 7 that this information is crucial for quantitative evaluations of the effects of parameter uncertainty.

From the posterior distribution, we observe strong correlations (> 0.5 in absolute value) between (σ, η_2, ρ_1) and other parameters. In the first counterfactual experiment, we artificially reverse the signs of these correlations while keeping the posterior means and variances of the marginal distributions untouched.[37] This change in correlation pattern leads to notable differences in uncertainty's effects on optimal tax policy: the change in optimal tax progressivity due to parameter uncertainty increases from 0.021 to 0.027; and the reduction in optimal tax level rises from 0.007 to 0.008.

Table 7: Importance of the Posterior Distribution

Posterior ($\Pi(\Theta)$)	ΔProgressivity	ΔLevel
True Posterior	0.021	-0.007
Counterfactual		
Reversed Correlation	0.027	-0.008
Uniform Distribution	0.029	-0.009

Notes: "Reversed Correlation" results are based on a posterior distribution with sign-reversed correlations between (σ, η_2, ρ_1) and other parameters. "Uniform Distribution" results are based on a uniform posterior distribution with the same posterior means and variances.

gain given uncertain parameters' distribution is difficult.

[37] In particular, for σ, η_2, and ρ_1, we replace each parameter value x with $2\mathbb{E}(x) - x$, where $\mathbb{E}(x)$ is the corresponding posterior mean.

In the second counterfactual experiment, we modify the shape of the marginal distributions of parameters to uniform distributions with the same means and variances, while maintaining the general correlation pattern between parameters.[38] This change of the posterior distribution again leads to significantly different evaluations about the uncertainty's effects on optimal tax policy: the increase in optimal tax progressivity reaches 0.029, and the reduction in optimal tax level rises to 0.009.

Since information about correlations between uncertain parameters and the shape of their distribution is often difficult to obtain through non-Bayesian methods, and it has been proven to be important through our counterfactual experiments, we propose that the Bayesian approach shall become the norm for quantitative studies in which parameter uncertainty is of primary concern.

B.2 Risk Preferences of Policymakers

In our benchmark analysis, policymakers are assumed to be risk-neutral with respect to the variations in welfare induced by parameter uncertainty. In this section, we investigate how the benchmark result may be affected by alternative risk preferences of policymakers.

Formally, we adjust the risk-preferences of policymakers by modifying the "utility function" of policymakers, i.e., $\Gamma(\cdot)$, in the optimal tax policy problem (5). In particular, we choose the CARA functional form for $\Gamma(\cdot)$:

$$\Gamma(X) = \begin{cases} \frac{1-e^{-\alpha X}}{\alpha} & \text{if } \alpha \neq 0, \\ X & \text{if } \alpha = 0, \end{cases} \tag{12}$$

where α is the parameter that controls the risk aversion of policymakers.[39] The larger is α, the more the policymakers dislike risk. When $\alpha = 0$, policymakers are risk-neutral, and we are back to the benchmark case.

Our benchmark analysis assumes that policymakers aim to maximize the wel-

[38] In particular, we replace each parameter value x with $\sqrt{3\text{Var}(x)}(2\text{cdf}(x) - 1) + \mathbb{E}(x)$, where $\mathbb{E}(x)$ and $\text{Var}(x)$ are the corresponding posterior mean and variance, and $\text{cdf}(x)$ is the cumulative distribution function of x. Note that the transformation is strictly increasing, and hence the correlation pattern between parameters is largely preserved, albeit not perfectly.

[39] We choose the CARA, not CRRA, functional form because welfare gain, i.e., X in (12), could be negative.

fare gain from tax reform relative to the status quo. An alternative welfare criterion is to minimize the welfare loss relative to the first-best scenario, as described in (11). Section 5.2 already noted that these two optimal tax problems are equivalent when policymakers are risk-neutral (hence why we do not differentiate them in the benchmark analysis), but it is no longer the case when policymakers are risk-averse.

For example, maintaining the status quo policy is a risk-free option when maximizing the welfare gain since welfare gain is always zero. However, when minimizing the welfare loss, the status quo policy is risky in the sense that the welfare loss of no reform compared to the first-best scenario is uncertain. Put another way, by doing nothing, policymakers could be giving up very little or a lot in potential welfare gain depending on the true state of parameters. In the following, we consider both types of welfare criteria in our analysis.[40]

Table 8 reports the optimal tax progressivity based on the posterior distribution under various degrees of policymakers' risk aversion and for both types of welfare criteria. We consider three degrees of risk aversion corresponding to $\alpha = 0$, 10, and 50. When maximizing the welfare gain, the risk of tax reform is higher when the new policy is further away from the status quo policy, and hence risk aversion of policymakers pushes the optimal tax policy towards the status quo policy, which means lower progressivity in our model. When minimizing the welfare loss, the pattern is different. Since the first-best tax policy depends on the true parameter values, a risk-free policy in this case must be parameter-contingent, which is infeasible in the presence of parameter uncertainty. Without a clear risk-free option, it is less straightforward how a higher risk aversion of policymakers would alter the optimal tax policy. Our quantitative results suggest that the optimal tax progressivity is more robust with respect to the degree of policymakers' risk aversion in this case.

Figure 8 shows how welfare measures change with tax progressivity for both types of welfare criteria with different degrees of risk aversion. In addition to reconfirming our findings in Table 8 about the optimal policy (i.e., the peaks and troughs of curves), one interesting observation is that when maximizing the welfare gain, the welfare gain from any tax reform that increases tax progressivity relative

[40]Note that when minimizing the welfare loss, we need to replace α with $-\alpha$ in (12).

Table 8: Optimal Tax Progressivity and Risk Preferences of Policymakers

	Welfare Criterion	
	Max Welfare Gain	Min Welfare Loss
Risk Neutral	0.148	0.148
Risk Aversion 10	0.141	0.154
Risk Aversion 50	0.132	0.150
Tail 10	0.128	0.177

Notes: "Risk Neutral", "Risk Aversion 10", and "Risk Aversion 50" correspond to the cases with $\alpha = 0$, 10, and 50. "Tail 10" corresponds to the case when the average of the worst 10% of possible outcomes is used as the objective.

to the status quo is lowered by the policymakers' risk aversion, whereas when minimizing the welfare loss, the welfare gain of such reform (i.e., reduction in welfare loss) increases with policymakers' risk aversion.

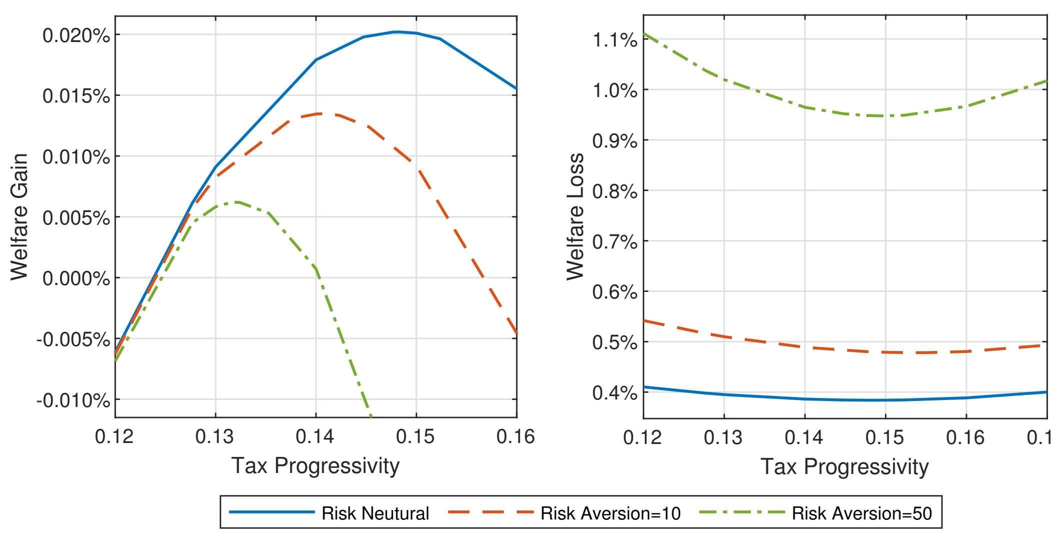

Figure 8: Welfare, Tax Progressivity, and Risk Preferences of Policymakers

Notes: This figure shows how welfare measures change with tax progressivity, when maximizing the welfare gain (left panel) and minimizing the welfare loss (right panel) under various degrees of policymakers' risk aversion. "Risk Neutral", "Risk Aversion 10", and "Risk Aversion 50" correspond to the cases with $\alpha = 0$, 10, and 50.

We also consider another form of policymakers' risk preferences focusing on the worst-case scenarios, specifically the worst 10% of possible outcomes from tax reform. When maximizing the welfare gain, we assume that the policymakers want to maximize the average welfare in the bottom 10% of the welfare distribution induced by parameter uncertainty. Similarly, when minimizing the welfare loss, the goal is to minimize the average welfare loss in the top 10% of the welfare loss distribution. The corresponding results are reported in Table 8 under the label "Tail 10".

C Supplementary Materials for Quantitative Analysis

C.1 Additional Quantitative Results

In this section, we provide supplementary results to the quantitative analysis in the main text. Figure 9 presents the estimated male and female log-wage trends over the life cycle. Table 9 reports the list of moment conditions employed in the limited-information Bayesian estimation and their values from the data and from the posterior distribution. Table 10 and 11 report the correlations among preference and wage parameters, respectively.

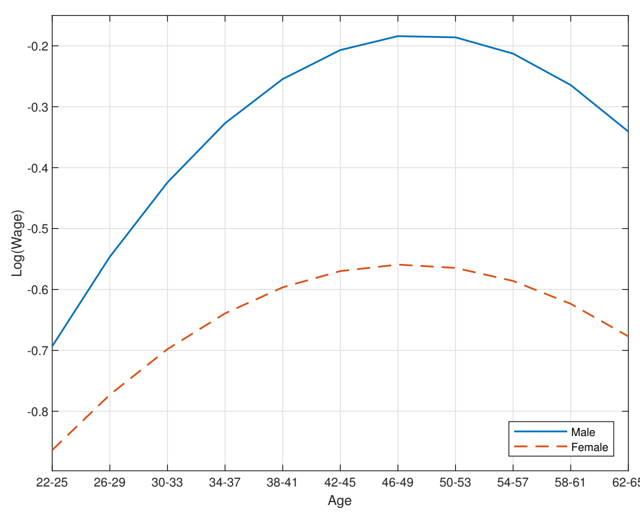

Figure 9: Male and Female Wage Trends

Notes: This figure plots the male (blue solid line) and female (red dashed line) log-wage trends over the life cycle estimated from the data.

Table 9: Moment Conditions

Moment	Data	Model
A. Wage Parameters		
$\mathbb{E}(\Delta w_{1,t}\Delta w_{1,t-1})$	-0.0264	-0.0270
$\mathbb{E}[(\Delta w_{1,t})^2]$	0.1332	0.1333
$\mathbb{E}(\Delta w_{2,t}\Delta w_{2,t-1})$	-0.0352	-0.0349
$\mathbb{E}[(\Delta w_{2,t})^2]$	0.1487	0.1484
$\mathbb{E}(\Delta w_{1,t}\Delta w_{2,t})$	0.0062	0.0062
$\mathrm{Var}(w_{1,1})$	0.2113	0.2094
$\mathrm{Var}(w_{2,1})$	0.2323	0.2316
$\mathrm{Cov}(w_{1,1}, w_{2,1})$	0.0473	0.0471
$\mathrm{Var}(\hat{w}_{1,1})$	0.0750	0.0750
$\mathrm{Var}(\hat{w}_{2,1})$	0.0605	0.0604
$\mathrm{Cov}(\hat{w}_{1,1}, \hat{w}_{2,1})$	0.0280	0.0279
B. Preference Parameters		
$\mathbb{E}[(\Delta c_t)^2]$	0.0711	0.0480
$\mathbb{E}(\Delta w_{1,t}\Delta y_{1,t})$	0.0988	0.1157
$\mathbb{E}(\Delta w_{2,t}\Delta y_{2,t})$	0.0777	0.1355
$\mathbb{E}[(\Delta y_{1,t})^2]$	0.1275	0.1236
$\mathbb{E}[(\Delta y_{2,t})^2]$	0.1962	0.1546
$\mathbb{E}(\Delta y_{1,t}\Delta y_{1,t-1})$	-0.0264	-0.0171
$\mathbb{E}(\Delta y_{2,t}\Delta y_{2,t-1})$	-0.0211	-0.0281
$\mathbb{E}(\Delta y_{1,t}\Delta c_t)$	0.0078	0.0229
$\mathbb{E}(\Delta y_{2,t}\Delta c_t)$	0.0022	0.0124
$\mathbb{E}(\Delta w_{1,t}\Delta c_t)$	0.0059	0.0234
$\mathbb{E}(\Delta w_{2,t}\Delta c_t)$	-0.0014	0.0145
$\mathbb{E}(\Delta y_{1,t}\Delta y_{2,t})$	-0.0001	-0.0174
$\mathbb{E}(\Delta w_{1,t}\Delta y_{2,t})$	-0.0008	-0.0040
$\mathbb{E}(\Delta w_{2,t}\Delta y_{1,t})$	0.0044	-0.0018
$\mathbb{E}[Y_{1,t}]$	1	0.9647
$\mathbb{E}[Y_{2,t} \mid H_{2,t} > 0]$	0.4809	0.4797
$\mathbb{E}[\mathbf{I}(H_{2,t} = 0)]$	0.1539	0.1604
$\mathbb{E}[H_{1,t}]$	1	0.9992
$\mathbb{E}[H_{2,t} \mid H_{2,t} > 0]$	0.7058	0.7286
$\mathbb{E}[A_t]$	0.8836	0.9114

Notes: "Model" results are the means of the posterior distributions of moments.

Table 10: Correlations Between Preference Parameters

	σ	η_1	η_2	ψ_1	ψ_2	f	δ
σ	1	0.05	-0.10	0.94	0.38	0.24	-0.37
η_1	0.05	1	-0.40	-0.04	0.35	0.33	0.25
η_2	-0.10	-0.40	1	-0.08	-0.91	-0.89	-0.10
ψ_1	0.94	-0.04	-0.08	1	0.36	0.25	-0.43
ψ_2	0.38	0.35	-0.91	0.36	1	0.88	-0.07
f	0.24	0.33	-0.89	0.25	0.88	1	-0.01
δ	-0.37	0.25	-0.10	-0.43	-0.07	-0.01	1

Table 11: Correlations Between Wage Parameters

	ρ_1	ρ_2	$\sigma^2_{v_1}$	$\sigma^2_{v_2}$	$corr_{v_1,v_2}$	$\sigma^2_{F_{1,1}}$	$\sigma^2_{F_{2,1}}$	$corr_{F_{1,1},F_{2,1}}$	$\sigma^2_{\alpha_1}$	$\sigma^2_{\alpha_2}$	$corr_{\alpha_1,\alpha_2}$
ρ_1	1	0.04	-0.52	0.03	0.11	-0.02	-0.02	-0.01	-0.12	-0.04	-0.01
ρ_2	0.04	1	-0.02	0.16	-0.09	0.02	-0.05	-0.02	-0.03	0.00	-0.03
$\sigma^2_{v_1}$	-0.52	-0.02	1	0.05	-0.08	-0.06	0.00	0.03	0.04	0.03	0.01
$\sigma^2_{v_2}$	0.03	0.16	0.05	1	-0.12	0.00	-0.01	-0.03	0.15	-0.04	-0.02
$corr_{v_1,v_2}$	0.11	-0.09	-0.08	-0.12	1	0.03	-0.07	-0.10	-0.11	0.02	0.02
$\sigma^2_{F_{1,1}}$	-0.02	0.02	-0.06	0.00	0.03	1	0.12	-0.15	0.08	0.12	0.04
$\sigma^2_{F_{2,1}}$	-0.02	-0.05	0.00	-0.01	-0.07	0.12	1	0.20	0.05	0.04	-0.11
$corr_{F_{1,1},F_{2,1}}$	-0.01	-0.02	0.03	-0.03	-0.10	-0.15	0.20	1	-0.02	0.00	0.08
$\sigma^2_{\alpha_1}$	-0.12	-0.03	0.04	0.15	-0.11	0.08	0.05	-0.02	1	0.15	0.13
$\sigma^2_{\alpha_2}$	-0.04	0.00	0.03	-0.04	0.02	0.12	0.04	0.00	0.15	1	0.10
$corr_{\alpha_1,\alpha_2}$	-0.01	-0.03	0.01	-0.02	0.02	0.04	-0.11	0.08	0.13	0.10	1

C.2 Measure Welfare Change in Consumption

We provide here the formulas for computing the welfare gain in consumption $W(\tau, \lambda, \Theta)$ in the optimal tax policy problem of Section 3.3. Following the convention, we assume that the hypothetical consumption transfers are proportional to household consumption before the tax reform, while household labor supply and public consumption remain the same. Given the CRRA utility function in private consumption, the proportional change in consumption required to achieve the same social welfare change as the tax reform is given by

$$\text{CEV}(\tau, \lambda, \Theta) \equiv \left(1 + \frac{\text{SWF}(\tau, \lambda, \Theta) - \text{SWF}(\tau_{sq}, \lambda_{sq}, \Theta)}{\text{VC}(\tau_{sq}, \lambda_{sq}, \Theta)}\right)^{1/(1-\sigma)} - 1.$$

Here $\text{VC}(\tau_{sq}, \lambda_{sq}, \Theta)$ is the weighted sum of expected lifetime utility from private consumption for a newborn cohort under the status quo tax policy $(\tau_{sq}, \lambda_{sq})$. The weights are the same as the Pareto weights $\omega(\mathbf{s})$ in the social welfare function.

The present value of all consumption transfers required is then:

$$W(\tau, \lambda, \Theta) \equiv \text{CEV}(\tau, \lambda, \Theta) \times \left[\sum_{t=1}^{T} \frac{\text{Consumption}_t(\tau_{sq}, \lambda_{sq}, \Theta)}{(1+r)^{t-1}}\right],$$

$$\text{Comsumption}_t(\tau_{sq}, \lambda_{sq}, \Theta) = \int_{\mathbf{s}} C_t(\mathbf{s}; \tau_{sq}, \lambda_{sq}, \Theta) d\Phi_t(\mathbf{s}; \tau_{sq}, \lambda_{sq}, \Theta),\ t = 1, \ldots, T,$$

where $C_t(\mathbf{s}; \tau_{sq}, \lambda_{sq}, \Theta)$ is household consumption, $\Phi_t(\mathbf{s}; \tau_{sq}, \lambda_{sq}, \Theta)$ is the distribution of households, and $\text{Consumption}_t(\tau_{sq}, \lambda_{sq}, \Theta)$ is total private consumption, all for age-t households under the status quo tax policy.

C.3 Computation

The household optimization problem is solved backwards using the endogenous grid method. With the extensive margin of female labor supply, for each iteration and each household state, the optimization problem is solved twice under two alternative scenarios: the current period female labor supply is strictly positive or zero. The final optimal policy is obtained by comparing the discounted utility achieved in these two scenarios.

The grid for asset has 100 grid points, and the distance between two adjacent grid points increases with the asset level such that the grid points are denser around the low asset levels where borrowing constraints are more likely to bind. The grid for the male and female earners' permanent wage components has 2 grid points in each dimension. The joint process of the two earners' persistent wage components is approximated by a discrete Markov process with age-dependent sets of states and transition matrices. The grid for the joint wage process has 11 points in each dimension, so there are in total 121 grid points at each age.

Since the computation burden of the optimal tax policy problem with parameter uncertainty is proportional to the number of posterior draws, we cannot afford using the empirical posterior distribution with 15,000 draws directly.[41] Hence to keep the computation burden manageable, we approximate the empirical posterior distribution with a sample of 30 i.i.d draws from it. We adjust the values of these draws such that the means and variances of the approximated distribution are exactly the same as those of the true posterior distribution. In particular, we replace the parameter value $\hat{\theta}$ of each draw by

$$\frac{\sigma_\theta}{\sigma_{\hat{\theta}}}(\hat{\theta} - \mu_{\hat{\theta}}) + \mu_\theta,$$

where μ_θ and σ_θ are the mean and standard deviation of parameter θ implied by the true posterior distribution; and $\mu_{\hat{\theta}}$ and $\sigma_{\hat{\theta}}$ are the sample mean and standard deviation of the unadjusted approximated distribution. Since the means and variances of the unadjusted distribution are already close to those of the true posterior distribution, the adjustments required to make them equal are rather minor. For robustness check, we double the number of sample draws for the approximated distribution and redo our baseline exercise: the change in optimal tax progressivity based on the approximated posterior distribution is less than 1e-3. Therefore, we conclude that increasing the number of sample draws further would not affect the results significantly.

[41] Notice that previous quantitative studies of optimal tax policy in the literature are equivalent to solving the problem with only 1 posterior draw. So the increase in computation burden here is non-trivial.