Optimal Redistribution with a Shadow Economy

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May 6, 2022

Abstract

We extend the theory of optimal redistributive taxation to economies with an informal sector. In particular, in our model workers can supply labor simultaneously to the formal and the informal sectors, which we call *moonlighting*. The optimal tax formula contains two novel terms capturing informality responses on an intensive and an extensive margin. Both terms decrease the optimal tax rates. We estimate the model with Colombian data and find that informality strongly reduces tax rates at all income levels. The possibility to migrate to entirely informal employment restricts tax rates at low and medium income levels, while the possibility of moonlighting is relevant at higher earnings.

Keywords: informal sector, moonlighting, income taxation, redistribution.

JEL Codes: H21, H26, J46.

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1. Introduction

Informal activity, broadly defined as any economic endeavor which evades taxation, accounts for a large fraction of economic activity in both developing and developed economies. The share of informal production in GDP is consistently estimated to be on average above 10% in high income OECD countries and above 30% in developing and transition countries, in extreme cases reaching 70% (Schneider and Enste 2000; Schneider et al. 2011). Globally, 2 billion workers are employed informally (ILO 2018). The shadow economy allows workers to earn income which is unobserved by the government. Intuitively, this additional margin of response to taxation makes income redistribution more difficult. Indeed, empirical studies document often large informality responses to tax reforms.[1] However, a theory of how the income tax schedule should depend on informality is missing.

Our aim is to fill this gap. We derive the optimal non-linear income tax schedule with a shadow sector and characterize how informality determines its shape. To verify the significance of our theoretical results, we estimate the model with Colombian data. Accounting for informality turns out to be quantitatively very important for the optimal policy.

Building on the seminal work of Mirrlees (1971), we consider a framework with heterogeneous agents equipped with distinct formal and shadow productivities. Workers face an idiosyncratic fixed cost of working in the shadow economy, which may reflect either ethical or technological constraints. The government observes only formal incomes and introduces a non-linear tax to maximize its redistributive welfare criterion. Importantly, we allow workers to supply labor simultaneously to the formal sector and the shadow sectors, which we call *moonlighting*. In this way we can study incentives of formal employees to have an informal side job. Informal secondary employment is common and accounts for a substantial fraction of informal workers in many countries.[2] Furthermore, evidence suggests that starting a tax-advantaged secondary job is an important margin of response to tax reforms (Tazhitdinova 2017).

Our main theoretical result is a sufficient statistics formula for the optimal tax schedule in the economy with an informal sector. The formula contains two novel

[1] A positive impact of income tax rates on tax evasion and informality has been documented in Brazil (Monteiro and Assunção 2012; Rocha et al. 2018), Russia (Gorodnichenko et al. 2009), Pakistan (Waseem 2018) and Denmark (Kleven et al. 2011).

[2] Out of all workers engaged in informal work, the share with a formal main job was more than 10% in Barbados, more than 20% in the Russian Federation and Lithuania (Hussmanns and Jeu 2002) and more than 50% in Poland (Statistics Poland 2019). In Brazil, 37% of secondary jobs are micro-enterprises and can be classified as informal (Henley et al. 2009).

terms due to informality responses on the extensive margin (getting an informal job) and the intensive margin (shifting hours between a formal and an informal job). The extensive margin responses are typically modeled as binary: working or not working. In our setting it would correspond to agents being able to work only formally or only informally and, as a result, would rule out moonlighting. Instead, we allow workers to moonlight, which means that they can complement formal earnings with additional income from an informal job. Intuitively, these responses can be important for workers with well-paid formal jobs who face high marginal tax rates and for whom transitioning to entirely informal employment is too costly. The possibility of moonlighting also gives rise to informality responses on the intensive margin—shifting hours between the formal main job and the informal secondary job. We find that moonlighting workers respond on the intensive margin differently than formal workers. First, the formal earnings of moonlighting workers are more elastic. Second, moonlighting workers would never choose formal earnings where the tax schedule is locally regressive, i.e. where the marginal tax rates are decreasing. If the tax schedule features regions of regressivity then, following a tax reform, moonlighting workers may respond on the intensive margin by jumping over a regressivity region to a discretely lower level of formal earnings. In contrast, formal workers rarely respond by jumping.[3] Even though informality responses may involve abrupt earnings changes, we summarize their impact on tax revenue with well-defined elasticities.

We analytically examine how informality affects the optimal tax rates in two ways. First, we fix the distribution of formal income and examine what happens if informality responses were ignored, e.g. because of the erroneous beliefs of policymakers. We find that ignoring informality responses would result in higher tax rates. In other words, correctly accounting for work incentives in the presence of the informal sector leads to lower optimal tax rates. Second, we fix model primitives, such as the distribution of productivities in the two sectors, and compare the optimal top tax rate in the model with and without the shadow economy. This comparison is more challenging since the income distribution is allowed to freely adjust to tax policy. We find that the optimal top tax rate is weakly lower in the model with a shadow economy. Once the top tax rate exceeds a certain tipping point, a large fraction of top earners joins the informal sector with a large loss of tax revenue. We show that it is never optimal to cross this tipping point, which implies an upper bound on the optimal top tax rate with an informal sector.

[3] Bergstrom and Dodds (2021) study jump responses in Mirrlees model with multi-dimensional heterogeneity.

We estimate the model with Colombian data. Colombia is an attractive case study for two reasons. First, it has a large informal sector: close to 60% of main jobs are informal. Second, the level of informality in Colombia is very close to the average for the whole Latin America.[4] We extract the information on formal and shadow incomes from the household survey and estimate the model by maximum likelihood. The model replicates well the empirical sorting of workers between the formal sector and the informal sector.

In our quantitative exercise we compare the optimal tax schedule with the tax schedules chosen when various informality responses are ignored. Importantly, in this comparison we allow for the endogenous adjustment of the income distribution. We find that the possibility of workers to migrate to entirely informal employment restricts tax rates at low and medium income levels, while the possibility of moonlighting is relevant at higher levels of income. Specifically, if all informality responses are ignored, the marginal tax rates are overshot at all income levels and in particular at the bottom, where they are too high by 70 percentage points or more. As a result, the shadow economy doubles in size relative to the optimum, which has catastrophic welfare consequences. If instead it is acknowledged that workers can move to the shadow economy and only the moonlighting responses are ignored, the tax rates at the bottom are approximately optimal, but the rates above the median formal income are too high—by up to 20 percentage points—when preferences for redistribution are strong. That is because incentives for moonlighting are important higher in the income distribution compared to incentives for switching from entirely formal to entirely informal employment. When preferences for redistribution are strong, ignoring moonlighting responses substantially increases the incidence of moonlighting among the most productive workers. Thus, it leads to a large welfare loss, equivalent to 2.4% drop in consumption.

Related literature. Kopczuk (2001) considers income taxation with tax avoidance, which can be reinterpreted as informality, and shows that the standard formula for the optimal linear tax is still valid. In contrast, our results imply that the standard formula for the optimal *non-linear* tax is no longer valid.[5] Piketty and Saez (2013) and Piketty et al. (2014) study linear and top income taxation with a possibility of shifting income between two tax bases, one of which could

[4]Based on ILO (2018), the national share of informal employment in total employment in Latin America has a mean of 58.3% and a median of 59%.

[5]Our settings is not identical to Kopczuk's, since we consider a fixed cost of shadow employment. In a previous working paper version (Doligalski and Rojas 2016), we show that the standard formula for the optimal non-linear tax is not valid even if we abstract from the fixed cost of shadow employment.

stand for an informal sector, yet they do not consider extensive margin responses. Selin and Simula (2020) derive the optimal non-linear tax schedules with income shifting, but they effectively rule out partial shifting which would correspond to moonlighting in our framework. Beaudry et al. (2009) study redistribution with informal sector when both formal income and formal hours worked are observed. We instead maintain the Mirrleesian assumption of unobserved hours worked.

Another approach to study tax evasion, originating with Allingham and Sandmo (1972), uses a framework with probabilistic audits and penalties, taking a tax rate as given. Andreoni et al. (1998) and Slemrod and Yitzhaki (2002) review this strand of literature. We take a complementary approach and study the optimal non-linear tax schedule conditional on fixed tax evasion abilities of workers. Although we do not model tax audits and penalties explicitly, they are a possible justification for different productivities in the formal and the shadow sectors. Thus, our results on the optimal taxation should be understood as taking the quality of tax enforcement as given. Some early results from merging both optimal taxation and optimal tax compliance policies were derived by Cremer and Gahvari (1996), Kopczuk (2001) and Slemrod and Kopczuk (2002). Leal Ordóñez (2014) and Di Nola et al. (2020) investigate tax and enforcement policies quantitatively in the dynamic incomplete markets models.

This paper is closely related to the literature on the optimal taxation with multiple sectors. Rothschild and Scheuer (2014) consider uniform taxation of multiple sectors when agents can work in many sectors simultaneously. Kleven et al. (2009), Scheuer (2014) and Gomes et al. (2017) study differential taxation of broadly understood sectors (e.g. individual tax filers and couples, employees and entrepreneurs), when agents can belong to one sector only. Jacobs (2015) studies a complementary problem when all agents work in all sectors at the same time. Our analysis differs in that we consider a particular case of differential taxation—only one sector is taxed—when agents face an idiosyncratic fixed cost of participating in one of the sectors. This structure implies that some agents can effectively work in one sector only, while others are unconstrained in supplying labor to two sectors simultaneously.

Emran and Stiglitz (2005) and Boadway and Sato (2009) study commodity taxation in the presence of informality. Both papers assume that commodity taxes affects only the formal sector.[6] Hence, provided that formal and shadow

[6] In principle, VAT taxation covers informal firms indirectly if they purchase intermediate goods from the formal firms. De Paula and Scheinkman (2010) show that exactly for this reason informal firms tend to make transactions with other informal firms. Bachas et al. (2020) discuss more evidence that informal enterprises do not remit consumption taxes.

goods are perfect substitutes, a consumption tax is equivalent to a proportional tax on formal income. Under these assumptions our focus on non-linear income tax is without loss of generality. Boadway et al. (1994) and Huang and Rios (2016) study the optimal tax mix in the opposite case, when the consumption tax cannot be evaded. A related literature on the optimal commodity taxation with home production (Kleven et al. 2000; Olovsson 2015) studies the case of non-perfect substitutability between market and home produced goods.

Structure of the paper. In the following section we introduce the framework and characterize the equilibrium for a given income tax. In Section 3 we derive the optimal tax formula and show that the informal sector reduces the optimal tax rates. Section 4 is devoted to the quantitative exploration of our theoretical results. The last section provides conclusions. Proofs are relegated to the appendix.

2. Framework

There is a continuum of agents with heterogeneous labor productivities. Each agent can work in the formal sector (formal economy), in the informal sector (shadow economy), or in both simultaneously (which we call *moonlighting*). The fundamental difference between the two sectors is that formal earnings are observed by the tax authority and can be used to determine individual income tax payments, while informal earnings are hidden and cannot be used to determine taxes. In addition, individual labor productivity can differ between the sectors and participation in the informal sector is subject to a fixed cost, which we describe below.

Individuals are heterogeneous with respect to two privately observed characteristics: a productivity type θ and a cost type κ. The productivity type θ determines the labor productivity in the formal economy $w^f(\theta)$ and in the shadow economy $w^s(\theta)$. Earnings from each sector are a product of the sectoral productivity and the labor supplied to that sector. We assume that both productivity functions are non-negative and continuously differentiable with respect to θ and that the formal productivity is strictly increasing. θ is drawn from finite interval $[\underline{\theta}, \bar{\theta}] \subseteq \mathbb{R}$ according to twice continuously differentiable cumulative distribution function $F(\theta)$ with density $f(\theta)$.[7] Note that the distribution of productivities is effectively one-dimensional: conditional on the formal productivity, all agents have the same shadow productivity. In Appendix C we extend our main result to the case of

[7]We allow for an unbounded productivity distribution, in which case $\lim_{\theta \to \bar{\theta}} w^f(\theta) = \infty$.

two-dimensional distribution of productivities.

The cost type κ is a fixed cost of engaging in informal employment. It can be interpreted either as a technological constraint on tax evasion or a utility cost of violating social norms.[8] Conditional on θ, the fixed cost is drawn from $[0, \infty)$ according to twice continuously differentiable cumulative distribution function $G_\theta(\kappa)$ with density $g_\theta(\kappa)$. For a model without the fixed cost of shadow employment, see the earlier working paper version (Doligalski and Rojas 2016).

The agents' utility over consumption c and labor n, net of the fixed cost of shadow employment, is $c - v(n)$, where v is increasing, strictly convex, twice differentiable and satisfies $v'(0) = 0$.[9] Using this quasi-linear preference structure, which follows Atkinson (1990) and Diamond (1998), we characterize the entire Pareto frontier which is invariant to any increasing transformation of the utility function. Hence, our results are applicable also with utility functions $\mathbb{G}(c - v(n))$, where $\mathbb{G}$ is a strictly increasing and concave function. Nevertheless, this approach rules out the income effect. The impact of the income effect on the optimal tax schedules is well understood since Saez (2001) and the analysis can be easily extended in this direction.

Assumption 1 below ensures that the *Spence-Mirrlees* single-crossing condition holds for all workers. Consequently, formal income is increasing in productivity type θ even if agents are working informally, which helps us to keep track of workers' responses to tax reforms. The single-crossing condition holds when the comparative advantage in shadow labor $\frac{w^s(\theta)}{w^f(\theta)}$ is decreasing with formal productivity. In Section 4 we verify that this assumption holds in the data for Colombia.

Assumption 1. *(Single-crossing condition)* $\frac{w^s(\theta)}{w^f(\theta)}$ *is strictly decreasing with* θ *or* $w^s(\theta) = 0$ *for all* θ*.*

Lemma 1. *The formal earnings of formal workers and of moonlighting workers are increasing with productivity type* θ*.*

[8] In principle, we could introduce a fixed cost of formal employment as well. This would correspond to what Magnac (1991) calls a segmentation approach to informal labor markets, according to which shadow workers are restricted from formal employment by various labor regulations. An alternative, competitive approach is that individuals sort between the two sectors according to their individual advantage, which corresponds more closely to our framework. Magnac (1991) shows that the data on married women in Colombia favor the latter, competitive approach. It has been documented that informality is not driven by entry costs to the formal sector also in other setting, e.g. in Argentina (Pratap and Quintin 2006), Brazil (Rocha et al. 2018) and Sri Lanka (De Mel et al. 2013).

[9] We assume that disutility from working depends only on the total labor supply and not on the split of labor between sectors. This gives us tractability when describing the earnings responses of moonlighting agents, since the cost of substituting the formal and the informal labor depends only on their respective productivities and the tax schedule.

2.1. Equilibrium income choices

Consider a potentially nonlinear, twice differentiable income tax schedule T with tax rates strictly lower than 100%.[10] Denote the after-tax income schedule by $R(y) = y - T(y)$. A worker of type (θ, κ) chooses formal earnings y^f and informal earnings y^s by solving the following maximization problem

$$V(\theta,\kappa) = \max_{y^f \geq 0, y^s \geq 0} R(y^f) + y^s - v\left(\frac{y^f}{w^f(\theta)} + \frac{y^s}{w^s(\theta)}\right) - \kappa \cdot \mathbb{1}(y^s > 0) \qquad (1)$$

where $V(\theta, \kappa)$ is the indirect utility function and $\frac{y^i}{w^i(\theta)}$ stands for the labor supplied to sector $i \in \{f, s\}$. The optimal income choices are not necessarily unique, for instance a worker with $w^f = w^s$ and $\kappa = 0$ who faces no income tax is always indifferent between supplying formal and informal labor. To have a clear-cut characterization of income choices, we introduce the following tie-breaking rule.

Assumption 2. *A worker who is indifferent between multiple formal income levels chooses the highest one.*

We denote the income choices which solve the worker's problem (1) under Assumption 2 by $\mathbb{y}^f(\theta, \kappa)$ and $\mathbb{y}^s(\theta, \kappa)$.

The fixed cost κ affects the worker's decision whether to participate in the shadow economy. Beyond this decision, income choices are unaffected by κ. This allows us to summarise the income choices of $\theta-$workers in the following way. Suppose that $\theta-$worker with fixed cost κ finds it optimal to participate in the shadow economy. Naturally, all $\theta-$workers with lower fixed cost will also choose to supply informal labor. It follows that there exists a threshold $\tilde{\kappa}(\theta)$ such that workers with fixed cost below the threshold join the shadow economy, while workers with fixed cost above the threshold remain fully formal. Define $\overline{y}^f(\theta)$ as the formal income of $\theta-$workers who choose to remain entirely formal. Define $\underline{y}^f(\theta)$ and $y^s(\theta)$ as the formal and the informal earnings, respectively, of $\theta-$workers who earns some informal income. Naturally, $\overline{y}^f(\theta) > \underline{y}^f(\theta)$. The value of threshold

[10] We rule out tax kinks and, hence, bunching of different types along the productivity dimension alone. This kind of bunching is already well understood (Mussa and Rosen 1978; Ebert 1992), it happens rarely and is more important in the setting without the fixed cost of shadow employment (Doligalski and Rojas 2016). We allow for all other bunching patterns, most importantly the bunching of agents with simultaneously different cost and productivity types, which happens when there are formal and moonlighting workers with the same formal earnings. Regarding the assumption of tax rates being below 100%, it is always satisfied in the optimum. Both assumptions combined imply that formal earnings of formal and moonlighting workers are strictly increasing with θ.

$\tilde{\kappa}(\theta)$ then follows from the indifference between participating or not in the shadow economy of $\theta-$worker with the fixed cost equal exactly $\tilde{\kappa}(\theta)$:

$$R\left(\underline{y}^f(\theta)\right) + y^s(\theta) - v\left(\frac{\underline{y}^f(\theta)}{w^f(\theta)} + \frac{y^s(\theta)}{w^s(\theta)}\right) - \tilde{\kappa}(\theta) = R\left(\overline{y}^f(\theta)\right) - v\left(\frac{\overline{y}^f(\theta)}{w^f(\theta)}\right). \quad (2)$$

It is possible that for some θ none of the workers choose to earn informal income—that may happen if the shadow productivity or the marginal tax rates are sufficiently low. In this case, we set $\underline{y}^f(\theta) = \overline{y}^f(\theta)$, $y^s(\theta) = 0$ and $\tilde{\kappa}(\theta) = 0$.[11]

The income choices of any type (θ, κ) then follow

$$\mathrm{y}^f(\theta,\kappa) = \begin{cases} \overline{y}^f(\theta) & \text{if } \kappa \geq \tilde{\kappa}(\theta) \\ \underline{y}^f(\theta) & \text{otherwise,} \end{cases} \qquad \mathrm{y}^s(\theta,\kappa) = \begin{cases} 0 & \text{if } \kappa \geq \tilde{\kappa}(\theta) \\ y^s(\theta) & \text{otherwise.} \end{cases} \quad (3)$$

Now let's characterize the income schedules $\overline{y}^f$, $\underline{y}^f$ and y^s. The first-order condition of the $\theta-$worker who works only in the formal sector pins down $\overline{y}^f(\theta)$:

$$\left(1 - T'\left(\overline{y}^f(\theta)\right)\right) \cdot w^f(\theta) = v'\left(\frac{\overline{y}^f(\theta)}{w^f(\theta)}\right). \quad (4)$$

According to this condition, the marginal return to formal labor—the product of the formal productivity and the net-of-tax rate—is equal to the marginal disutility from labor. Thus, the worker cannot gain by marginally adjusting formal labor.

Suppose that some $\theta-$workers are working only in the shadow economy. Then $\underline{y}^f(\theta) = 0$ and $y^s(\theta) > 0$, and it must be the case that

$$\left(1 - T'(0)\right) \cdot w^f(\theta) < v'\left(\frac{y^s(\theta)}{w^s(\theta)}\right) = w^s(\theta). \quad (5)$$

By the equality on the right-hand side the return to informal labor, given by $w^s(\theta)$, is equal to the marginal disutility from labor. Thus, there are no gains to be made from marginally adjusting informal labor supply. The inequality on the left ensures that the worker also cannot benefit on the margin from starting to work formally.

Finally, suppose that some $\theta-$workers are moonlighting, i.e. working in the

[11] Equivalently, we can define these objects as $\overline{y}^f(\theta) = \lim_{\kappa\to\infty} \mathrm{y}^f(\theta,\kappa)$, $\underline{y}^f(\theta) = \mathrm{y}^f(\theta, 0)$, $y^s(\theta) = \mathrm{y}^s(\theta, 0)$ and $\tilde{\kappa}(\theta) = V(\theta, 0) - \lim_{\kappa\to\infty} V(\theta,\kappa)$, for all θ.

two sectors simultaneously: $\underline{y}^f(\theta) > 0$ and $y^s(\theta) > 0$. Their income choices satisfy

$$\left(1 - T'\left(\underline{y}^f(\theta)\right)\right) \cdot w^f(\theta) = v'\left(\frac{\underline{y}^f(\theta)}{w^f(\theta)} + \frac{y^s(\theta)}{w^s(\theta)}\right) = w^s(\theta). \tag{6}$$

Intuitively, in this case the worker cannot gain by either *(i)* adjusting only formal labor or *(ii)* adjusting only informal labor or *(iii)* shifting labor between the two sectors while keeping total labor supply fixed.[12]

The first-order condition of moonlighting workers has two important implications. First, the right-hand equality means that the total labor supply of a moonlighting worker is fully determined by the shadow productivity and, hence, cannot be affected by taxes. What taxes affect is only the sectoral split of labor. Second, moonlighting is closely related to tax progressivity. Condition (6) implies that $T'(\underline{y}^f(\theta)) = 1 - \frac{w^s(\theta)}{w^f(\theta)}$, where the right-hand side is strictly increasing with θ by Assumption 1. Thus, the marginal tax rates faced by moonlighting workers are strictly increasing with their productivity type. The proposition below explores the implications of this result. We show that moonlighting happens only where the tax is strictly progressive, i.e. has strictly increasing marginal tax rates.

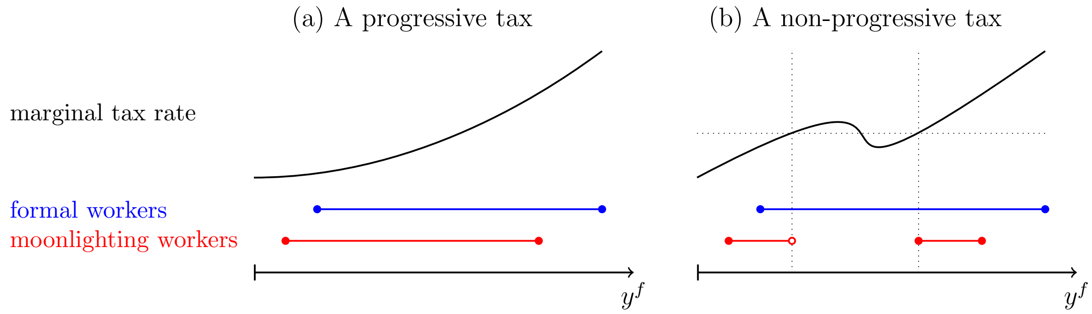
Proposition 1. *If the tax schedule is weakly regressive locally at some $y > 0$, i.e. $T''(y) \leq 0$, then there are no moonlighting workers with formal earnings y.*

The intuition is that workers will be moonlighting if the marginal benefit to supplying formal labor relative to informal labor is decreasing. In that case workers supply formal labor at first, but as the marginal benefit decreases sufficiently, they switch to the informal labor. That is exactly what happens when the tax schedule is progressive: low marginal tax rates at low income levels encourage formal labor at first, but high tax rates at higher levels discourage it.

What happens with moonlighting when the tax schedule is neither progressive nor regressive everywhere, but has regions of local progressivity and regressivity? Empirical income tax and transfer schedules, which typically have increasing statutory income tax rates, often become locally regressive where transfers are phased-out. By Proposition 1, no moonlighting worker will be found in the regions of local regressivity. If such regions are surrounded by regions of local progressivity, then the formal income schedule of moonlighting workers can become discontinuous, as depicted in Figure 1.

[12] Conditions (5) and (6) bound the marginal rate of substitution from below by $w^s(\theta)$. Similar constraints were found in other setting with hidden side trades, e.g. hidden saving, see Ábrahám and Pavoni (2005) and Golosov and Tsyvinski (2007).

Figure 1: Tax progressivity and continuity of $\underline{y}^f(\cdot)$



Note: The horizontal lines indicate that there are workers of a given kind at a given formal income level.

Although tax regressivity may lead to a discontinuity in the formal income schedule of moonlighting workers, their indirect utility function must remain continuous, which yields an additional equilibrium condition.[13] Suppose that $\underline{y}^f(\cdot)$ increases discontinuously at θ_d and denote the left limit at θ_d by $\underline{y}^f(\theta_d^-)$, so that we have $\underline{y}^f(\theta_d^-) < \underline{y}^f(\theta_d)$.[14] In equilibrium it must be the case that

$$\lim_{\theta \uparrow \theta_d} V(\theta, \kappa) = V(\theta_d, \kappa) \text{ for all } \kappa < \tilde{\kappa}(\theta), \tag{7}$$

since otherwise some types in the neighborhood of θ_d could improve by jumping across the income discontinuity. It is useful to rewrite this condition as

$$\frac{T(\underline{y}^f(\theta_d)) - T(\underline{y}^f(\theta_d^-))}{\underline{y}^f(\theta_d) - \underline{y}^f(\theta_d^-)} = T'(\underline{y}^f(\theta_d)). \tag{8}$$

Thus, the average tax rate on incomes between $\underline{y}^f(\theta_d^-)$ and $\underline{y}^f(\theta_d)$ is equal to the marginal tax rate $T'(\underline{y}^f(\theta_d))$. Note that while the sectoral split of labor changes discontinuously at θ_d, the total labor supply remains continuous, as it is pinned down by $w^s(\theta)$—recall condition (6). Condition (8) ensures then that the increase of formal after-tax income is exactly offset by the reduction of informal income such that consumption—and, hence, utility—remains continuous as well.[15]

In principle, the income schedule of formal workers also can be discontinuous. This happens when tax regressivity is strong enough such that the second-order condition of formal workers ceases to hold as a strict inequality—see Bergstrom

[13] By Corolarry 1 in Milgrom and Segal (2002) the value function is (absolutely) continuous.

[14] By Assumption 2 $\underline{y}^f(\cdot)$ is right continuous and, hence, $\underline{y}^f(\theta_d^+) = \underline{y}^f(\theta_d)$.

[15] As formal earnings increase from $y^f(\theta_d^-)$ to $y^f(\theta_d)$, formal after-tax income increases by $R(y^f(\theta_d)) - R(y^f(\theta_d^-))$ and the shadow income decreases by $\frac{w^s(\theta_d)}{w^f(\theta_d)}(y^f(\theta_d) - y^f(\theta_d^-))$. Requiring that the two are equal and using (6) yields (8).

and Dodds (2021) for a detailed analysis of such case. For simplicity of exposition we abstract from such possibility in the theoretical analysis with the following assumption. We verify that it holds in all our quantitative exercises.

Assumption 3. *The income schedule of formal workers $\overline{y}^f(\cdot)$ is continuous and the utility-maximizing earnings level of formal $\underline{\theta}-$worker is unique.*

3. Optimal tax schedule

In this section we will derive and characterize the optimal tax schedule. We consider a general social welfare function

$$\mathcal{W} = \int_{\underline{\theta}}^{\bar{\theta}} \int_0^{\infty} \lambda(\theta,\kappa) \cdot V(\theta,\kappa) dG_{\theta}(\kappa) dF(\theta). \tag{9}$$

We normalize the Pareto weights λ such that their population average is 1, which implies that they coincide with the marginal social welfare weights.[16] The tax schedule is optimal if it maximizes the social welfare function subject to the government budget constraint

$$\mathcal{TR} = \int_{\underline{\theta}}^{\bar{\theta}} \int_0^{\infty} T(\mathrm{y}^f(\theta,\kappa)) dG_{\theta}(\kappa) dF(\theta) \geq E, \tag{10}$$

where E stands for exogenous government expenditures. By finding the optimal tax schedule for arbitrary welfare weights, we recover the entire Pareto frontier of the model without income effects.[17]

From now on we will focus on the endogenous distribution of formal income. Denote the cdf and the density of formal income by H and h, respectively. We can decompose it into (scaled) cdf of earnings of formal workers H^f and (scaled) cdf of formal earnings of workers with some shadow income H^s, such that $H = H^f + H^s$,

[16] The marginal social welfare weight describes the welfare impact of marginally increasing consumption of a given agent, expressed in the units of tax revenue (see e.g. Piketty and Saez 2013). In our environment it is equal to $\lambda(\theta,\kappa)/\eta$, where η is the multiplier of the gov. budget constraint. It is easy to show that at the optimum η is equal to the average Pareto weight.

[17] Suppose that the social welfare function is $\int_{\underline{\theta}}^{\overline{\theta}} \int_0^{\infty} \mathbb{G}\left(V(\theta,\kappa)\right) dG_{\theta}(\kappa) dF(\theta)$, where $\mathbb{G}$ is an increasing and differentiable function. $\mathbb{G}$ is typically assumed to be strictly concave and it can represent either the decreasing marginal utility of consumption or the social taste for equality. In this case we find the optimal tax schedule iteratively. Start with an initial guess of the Pareto weights. In each step, find the optimal tax schedule and the indirect utility function V given the Pareto weights and set the new Pareto weights—to be used in the next step—according to $\lambda(\theta,\kappa) = \mathbb{G}'\left(V(\theta,\kappa)\right)$.

with the corresponding (scaled) densities h^f and h^s.[18] Denote the average welfare weight at formal earnings y by $\overline{\lambda}(y)$.

We derive the optimal tax schedule with the tax perturbation approach which originates from Saez (2001) and was further refined by Golosov et al. (2014) and Jacquet and Lehmann (2021). Consider a status quo tax schedule T and a new tax schedule $T + \mu \cdot \mathrm{d}T$ where the schedule $\mathrm{d}T$ indicates the *direction* of the tax reform and the scalar μ controls the *size* of the reform. We describe the impact of arbitrary tax reforms on the equilibrium outcomes with a Gateaux derivative. The Gateaux derivative of some functional $T \mapsto Z[T]$ in the direction $\mathrm{d}T$ is defined as

$$\mathrm{d}Z[T, \mathrm{d}T] = \lim_{\mu \to 0} \frac{Z[T + \mu \cdot \mathrm{d}T] - Z[T]}{\mu}. \tag{11}$$

For instance, consider formal earnings $\mathsf{y}^f(\theta, \kappa)$ as a functional of the tax schedule. $\mathrm{d}\mathsf{y}^f(\theta, \kappa)[T, \mathrm{d}T]$ informs us about the first-order impact of a small reform in the direction $\mathrm{d}T$ on the formal earnings of worker with type (θ, κ). Typically we omit the arguments and write it simply as $\mathrm{d}\mathsf{y}^f(\theta, \kappa)$.

To use Gateaux derivatives we need to ensure that such derivatives exist. There are two potential issues. First, the formality threshold $\tilde{\kappa}(\theta)$ is bounded from below by 0 and, thus, can be non-differentiable with respect to tax reforms at the bound. Intuitively, if nobody works in the shadow economy to start with, then increasing taxes can increase informality, but decreasing taxes cannot reduce it. Second, some moonlighting workers respond by jumping to a discretely different formal income level and their formal earnings are not differentiable. Lemma 2 ensures that the Gateaux derivative of the aggregate tax revenue $\mathcal{TR}$ exists nonetheless. To address the first issue, we show that almost everywhere threshold $\tilde{\kappa}(\theta)$ either has a Gateaux derivative or it does not affect tax revenue to the first order. To address the second, we express $\mathcal{TR}$ as the sum of integrals over the regions where income responses are differentiable, with jump responses accounted for by the endogenous edges of the integration regions. We then apply Leibniz integral rule to show that each of the integrals, and hence $\mathcal{TR}$ as a whole, has a Gateaux derivative.[19]

[18] $H^f(\cdot)$ and $H^s(\cdot)$ are *scaled* cdfs as they do not converge to 1 as $y \to \infty$ but rather to the shares of formal and non-formal workers in total employment, respectively.

[19] Golosov et al. (2014) ensures that $\mathrm{d}\mathcal{TR}$ exists by assuming sufficient smoothness of income choices with respect to tax reforms. Jacquet and Lehmann (2021) use implicit function theorem to show that income choices are differentiable when jump responses are ruled out. Hendren (2019) speculates that $\mathrm{d}\mathcal{TR}$ may exist even with jump responses, but does not prove it. To the best of our knowledge, Bergstrom and Dodds (2021) are the first to use Leibniz integral rule to obtain $\mathrm{d}\mathcal{TR}$ with jump responses.

Lemma 2. *The Gateaux derivative of the aggregate tax revenue $\mathcal{TR}$ in an arbitrary direction* $\mathrm{d}T \in \mathcal{C}^2$ *exists.*

Consider a tax reform in direction $\mathrm{d}T$. The reform affects the social welfare and the tax revenue. The latter impact can be decomposed into the mechanical effect, as well as the behavioral effects due to: *(i)* intensive margin responses of formal and moonlighting workers, and *(ii)* extensive margin responses due to workers changing their informality status. We describe these effects below and then collect them into the optimal tax formula. The detailed derivations are available in Appendix B.

Mechanical and welfare effects. The tax reform increases tax level at formal earnings y by $\mathrm{d}T(y)$, which mechanically increases tax revenue. The impact on the utility of each agent earning y is exactly $-\mathrm{d}T(y)$, since behavioral responses have no first-order utility impact by the envelope theorem. The social welfare impact is then obtained by multiplying the utility impact with the average marginal social welfare weight $\overline{\lambda}(y)$. Integrating over the entire income distribution yields the mechanical and welfare impacts of the reform:

$$ME = \int_0^\infty \mathrm{d}T(y)\; dH(y), \qquad WE = -\int_0^\infty \overline{\lambda}(y) \cdot \mathrm{d}T(y)\; dH(y). \tag{12}$$

Intensive margin responses. Formal workers adjust their earnings on the intensive margin in response to changes of the marginal tax rates $\mathrm{d}T'$. The tax revenue loss at earnings level y is standard and equal to

$$T'(y) \cdot \tilde{\varepsilon}^f(y) \cdot y \cdot \frac{\mathrm{d}T'(y)}{1 - T'(y)}, \quad \text{where } \tilde{\varepsilon}^f(y) = \left(\frac{1}{\varepsilon(y)} + \frac{T''(y) \cdot y}{1 - T'(y)} \right)^{-1}. \tag{13}$$

$\tilde{\varepsilon}^f(y)$ is the elasticity of earnings of formal workers with respect to the net-of-tax rate $1 - T'(y)$. It depends both on $\varepsilon(y)$, the elasticity along the *linear* tax schedule or the Frisch elasticity, and the local tax curvature. With a locally progressive tax ($T''(y) > 0$), income increase in response to a tax rate cut is dampened, as higher income leads to a higher tax rate. Hence, local tax progressivity (resp. regressivity) reduces (resp. increases) the elasticity of income.

Suppose that there are some moonlighting workers with formal income y and that their formal earnings schedule is locally continuous. The tax revenue loss due to the reduction of formal earnings of moonlighting workers is equal to

$$T'(y) \cdot \tilde{\varepsilon}^s(y) \cdot y \cdot \frac{\mathrm{d}T'(y)}{1 - T'(y)}, \quad \text{where } \tilde{\varepsilon}^s(y) = \frac{1 - T'(y)}{T''(y) \cdot y}. \tag{14}$$

The formal earnings responses of moonlighting workers are summarized by elasticity $\tilde{\varepsilon}^s(y)$.[20] We find that formal earnings of moonlighting workers are more elastic than these of exclusively formal workers: $\tilde{\varepsilon}^s(y) > \tilde{\varepsilon}^f(y)$. The intuition behind this results is tightly related to the first-order conditions (4) and (6). An increase of the tax rate reduces the marginal benefit from supplying formal labor for formal and moonlighting workers in a symmetric manner. Both formal and moonlighting workers will reduce formal labor supply until the marginal benefit increases up to the level of the marginal cost. The difference between them is in the determination of the marginal cost of formal labor. For the formal worker the marginal cost is the marginal disutility of labor $v'(\cdot)$, which decreases as the total labor supply is reduced. For the moonlighting worker, however, the total labor supply is fixed and the tax reform affects only the sectoral split of labor. The marginal cost for these workers is the forgone informal income, which is equal to the shadow productivity $w^s(\theta)$. Given that the marginal cost of the moonlighting workers is constant in formal labor, rather than decreasing as in the case of the formal workers, they will adjust formal labor more than formal workers.

As we discussed, the formal income schedule of the moonlighting workers can become discontinuous when the tax schedule is not fully progressive. Suppose that formal earnings of moonlighting workers increase discontinuously between levels $\underline{s}$ and $\overline{s}$. By condition (8), the workers at these income levels are indifferent between earning $\underline{s}$ or $\overline{s}$. Thus, a tax reform that changes the relative tax burden at these earnings—e.g. an increase of the marginal tax rate at some earnings $y \in (\underline{s}, \overline{s})$—will imply a discrete jump of workers between $\underline{s}$ and $\overline{s}$, as depicted in Figure 2. Suppose that a tax reform increases the relative tax burden by $\mathrm{d}\left[T(\overline{s}) - T(\underline{s})\right]$, which affects the higher level of earnings $\overline{s}$ by $\mathrm{d}\overline{s}$. As a result, the measure $\mathrm{d}\overline{s} \cdot h^s(\overline{s})$ of moonlighting workers reduce formal earnings by a discrete amount $\overline{s} - \underline{s}$. In Appendix B we show that formal earnings loss due to these jump responses satisfies

$$-\left(\overline{s} - \underline{s}\right) \cdot \mathrm{d}\overline{s} \cdot h^s(\overline{s}) = \tilde{\varepsilon}^s(\overline{s}) \cdot \overline{s} \cdot h^s(\overline{s}) \cdot \frac{\mathrm{d}\left[T(\overline{s}) - T(\underline{s})\right]}{1 - T'(\overline{s})}. \tag{15}$$

We find that although each individual earnings response is discrete, the sum of responses is described with a well-behaved elasticity. The intuition is that although each jumping individual reduces formal earnings by $\overline{s} - \underline{s}$, the measure of jumping individuals is inversely proportional to $\overline{s} - \underline{s}$. Hence, the total formal income reduction is independent of the size of the jump. Furthermore, the

[20] By Proposition 1 we know that $T''(y) > 0$. Otherwise, there would be no moonlighting workers with such earnings.

elasticity describing the jumping responses is exactly the same as the elasticity of moonlighting workers responding marginally, $\tilde{\varepsilon}^s$. It follows from the indifference condition (8) which states that the average tax rate over earnings interval $[\overline{s}, \underline{s}]$ is equal to the marginal tax rate at $\overline{s}$. Using this equality of the average and the marginal tax rates, we can represent the tax revenue loss from these jump responses as

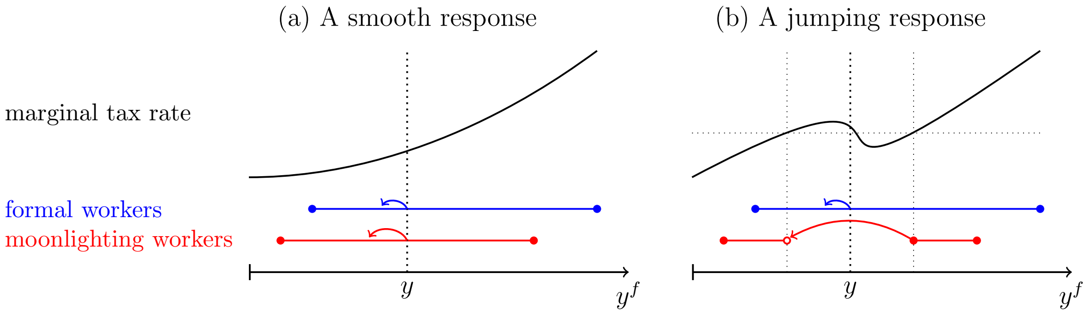
$$-\left(T(\overline{s})-T(\underline{s})\right)\cdot \mathrm{d}\overline{s}\cdot h^s(\overline{s}) = T'(\overline{s})\cdot\tilde{\varepsilon}^s(\overline{s})\cdot\overline{s}\cdot h^s(\overline{s})\cdot\frac{\mathrm{d}\left[T(\overline{s})-T(\underline{s})\right]}{1-T'(\overline{s})}. \tag{16}$$

Collecting the terms, intensive margin responses (either smooth responses or jumps) have the following impact on the aggregate tax revenue:

$$\begin{aligned} BE_{int} = &-\int_0^\infty \frac{T'(y)}{1-T'(y)}\cdot y\cdot\left(\tilde{\varepsilon}^f(y)\cdot h^f(y)+\tilde{\varepsilon}^s(y)\cdot h^s(y)\right)\cdot \mathrm{d}T'(y)\; dy \\ &- \sum_{(\overline{s},\underline{s})\in D}\frac{T'(\overline{s})}{1-T'(\overline{s})}\cdot\tilde{\varepsilon}^s(\overline{s})\cdot\overline{s}\cdot h^s(\overline{s})\cdot \mathrm{d}\left[T(\overline{s})-T(\underline{s})\right], \end{aligned} \tag{17}$$

where set D contains pairs of income levels between which the moonlighting workers jump.[21] The first term describes the tax revenue impact of the marginal responses of the formal and the moonlighting workers, respectively. The second term captures the impact of the jumping responses of moonlighting workers.

Figure 2: Intensive margin responses of moonlighting workers



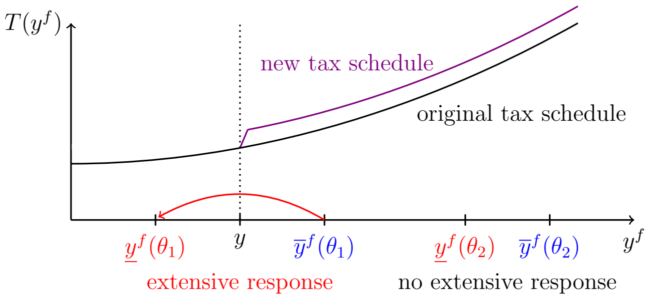
Note: The horizontal lines indicate that there are workers of a given kind at a given formal income level. The arrows represent the formal income responses to an increase of $T'(y)$.

Extensive margin responses. These responses consist of switching from working exclusively formally to either moonlighting or working exclusively informally. The possibility of moonlighting means that the extensive margin responses

[21]Formally, $D = \{(\overline{s},\underline{s})\in\mathbb{R}^2_+ : \underline{s} = \lim_{\theta\uparrow\theta_d}\underline{y}^f(\theta) < \lim_{\theta\downarrow\theta_d}\underline{y}^f(\theta) = \overline{s} \text{ for some } \theta_d\in[\underline{\theta},\overline{\theta}]\}$. Since $\underline{y}^f$ is increasing, it has countably many discontinuity points and, hence, D is countable.

are not equivalent to responses on the formal participation margin. In particular, a worker who switches from exclusively formal employment to moonlighting continues to work in the formal sector and retains a fraction of formal earnings. It has important implications for the incidence of the extensive margin responses, as depicted in Figure 3. The depicted tax reform increases the tax burden for workers with incomes above y. Consequently, incentives for informality increase for formal agents with earnings above y who, conditional on joining the shadow economy, would earn less than y in the formal sector. On the other hand, incentives for informality are unaffected for formal workers who, even if they moonlighted, would have formal income above y—they would pay a higher tax either way.

Figure 3: The incidence of extensive margin responses



Note: An increase of $T'(y)$ triggers an extensive margin response for workers with productivity type θ_1, but not for workers with productivity type θ_2.

To capture the tax revenue impact of the extensive margin responses, consider formal workers with earnings z. Denote by $\rho(z) = \underline{y}^f(\overline{y}^{f^{-1}}(z))$ their formal earnings if they had lower realisation of fixed cost of informal employment κ and (potentially) worked informally.[22] Note that $\rho(z)$ can be zero or positive. Now we can define the *tax burden of staying formal* as $\Delta T(z) = T(z) - T(\rho(z))$. The tax revenue impact of the extensive margin responses of these workers is then

$$\Delta T(z) \cdot \mathrm{d}h^f(z) = -\Delta T(z) \cdot \pi(z) \cdot h^f(z) \cdot \mathrm{d}\Delta T(z), \tag{18}$$

where $\pi(z)$ is the semi-elasticity of the density of formal workers with respect to the tax burden of staying formal, defined as $\pi(z) = \frac{g_\theta(\tilde{\kappa}(\theta))}{1-G_\theta(\tilde{\kappa}(\theta))}\frac{1}{h^f(z)}$ for θ such that $\overline{y}^f(\theta) = z$. Thus, the extensive margin responses are more costly in terms of government revenue when the tax burden of staying formal is higher, and when the density of agents at the threshold $\tilde{\kappa}(\theta)$ is higher, which translates into larger

[22] By assumptions made $\overline{y}^f$ is strictly increasing and, thus, its inverse function $\overline{y}^{f^{-1}}$ exists.

semi-elasticity of earnings density $\pi(z)$. Aggregating extensive responses across all income levels, we have

$$BE_{ext} = -\int_0^\infty \Delta T(z) \cdot \pi(z) \cdot h^f(z) \cdot \mathrm{d}\Delta T(z)\, dz. \tag{19}$$

Optimal tax formula. At the optimal tax schedule no small tax reform can result in a gain in the welfare-adjusted tax revenue. Hence, the sum of all the effects of the tax reform needs to be zero:

$$ME + WE + BE_{int} + BE_{ext} = 0 \tag{20}$$

for an arbitrary direction of the tax reform. The following theorem expresses this condition as a Diamond-Saez formula for economies with an informal sector.

Theorem 1. *Suppose that the optimal tax schedule is twice continuously differentiable. The optimal tax rate at earnings y satisfies*

$$\begin{aligned} &\frac{T'(y)}{1-T'(y)} \cdot \tilde{\varepsilon}^f(y) \cdot y \cdot h^f(y) + \frac{T'(\overline{s}(y))}{1-T'(\overline{s}(y))} \cdot \tilde{\varepsilon}^s(\overline{s}(y)) \cdot \overline{s}(y) \cdot h^s(\overline{s}(y)) \\ &\qquad = \int_y^\infty \left[1-\bar{\lambda}(z)\right] dH(z) - \int_y^\infty \Delta T(z) \cdot \pi(z) \cdot \mathbb{1}(\rho(z) \le y)\, dH^f(z) \end{aligned} \tag{21}$$

where $\overline{s}(y)$, equal to $\min\{z \in Im(\underline{y}^f) : z \geq y\}$ if min. exists and 0 otherwise, indicates the formal earnings of moonlighting workers distorted by a raise of $T'(y)$.

Formula (21) equates costs and benefits of increasing marginal tax rate $T'(y)$. The left-hand side consists of the deadweight loss from distorting the formal workers and the moonlighting workers. Note that we combine the deadweight loss from smooth and jumping responses of moonlighting workers into a single term by using mapping $y \mapsto \overline{s}(y)$ which points to formal earnings where the distorted moonlighting workers are located. The deadweight loss terms increase in *(i)* the marginal tax rate, as the reduction in formal income implies a higher tax loss if it is taxed at the higher rate, *(ii)* the density of formal income and *(iii)* the formal income reduction per worker in response to a higher tax rate, i.e. the product of formal income and the income elasticity.

There are two important differences between the deadweight loss terms of formal and moonlighting workers. The first difference relates to the location of responses. The raise of $T'(y)$ triggers intensive margin responses of formal workers with earnings y. In contrast, the intensive margin responses of moonlighting workers happen at formal earnings level $\overline{s}(y)$ which can be strictly greater than y. In particular, if $\overline{s}(y) = y$ then the moonlighting workers respond smoothly, while in the case of $\overline{s}(y) > y$ they respond by jumping to a discretely lower formal earnings. The second difference relates to the size of responses. Conditional on the local progressivity of the tax schedule, the moonlighting workers are more elastic than the formal workers. Thus, *ceteris paribus*, increasing tax rates at incomes which are earned predominantly by moonlighting workers is more distortionary.

The last term on the right-hand side represents the tax loss from increased participation in the shadow economy. Importantly, moonlighting modifies the incidence of these extensive margin responses. Absent moonlighting, an increase of $T'(y)$ increases incentives for informality for all formal workers earning more than y. With moonlighting, the incentives for informality increase only at some formal earnings levels $z > y$—those for which $\rho(z) \leq y$ holds. Intuitively, if formal workers earning $z > y$ retained formal income of $\rho(z) > y$ even if they started moonlighting, then the raise of $T'(y)$ would not affect their incentives to take up an informal job. The remaining terms on the right-hand side of the formula capture the mechanical and welfare impacts of the reform, which are standard.

The novelty of the tax formula is due to the moonlighting responses, namely complementing formal earnings with income from an informal job. There are other settings that give rise to phenomena similar to moonlighting where such formula could be applied, e.g. the model of home production, or the problem of a local tax authority with residents that can work partly outside its jurisdiction as seasonal workers—see Mirrlees (1982) for an early investigation of a similar problem.

3.1. How does a shadow economy affect optimal tax rates?

We examine the impact of a shadow economy on the optimal tax rates in two ways, similarly to the approach of Scheuer and Werning (2017). First, we fix the formal income distribution and other sufficient statistics and compare the prescription of the optimal tax formula with the tax schedules that would be chosen by the tax authority which believed certain informality responses do not happen. Tax schedules chosen under such beliefs can be described with well-known formulas from the literature. This analysis is most informative for choosing tax policy based on a given, observed formal income distribution. Second, we compare the optimal top tax rate with and without a shadow economy for given model primitives while allowing the formal income distribution to adjust. This comparison is useful for the counterfactual analysis. It informs us how the optimal top tax rate would change if we could costlessly shut down the informal sector.

3.1.1. Comparison for a fixed formal income distribution

Taking the income distribution and other sufficient statistics as given, we will compare the prescriptions of the optimal tax formula and two other formulas, corresponding to different beliefs regarding the informality, which we describe below.

In the first case the tax authority acknowledges the mobility between the formal and the informal sectors, but ignores the possibility of moonlighting. The tax formula corresponding to such beliefs is

$$\frac{T_I'(y)}{1-T_I'(y)} \cdot \bar{\varepsilon}(y) \cdot y \cdot h(y) = \int_y^\infty \left[1-\bar{\lambda}(z)\right] dH(z) - \int_y^\infty \Delta T(z) \cdot \pi(z) \cdot \mathbb{1}(\rho(z)=0)\; dH^f(z), \quad (22)$$

where $\bar{\varepsilon}(y)$ is the average formal earnings elasticity at formal income y and $\pi(z) \cdot \mathbb{1}(\rho(z) = 0)$ is the semi-elasticity of participation in the formal labor market at formal income z with respect to tax burden at z. The indicator function makes sure that only responses which reduce formal earnings to zero are accounted for. Such formula was derived by Saez (2002) and Jacquet et al. (2013) in the model with intensive margin responses and endogenous participation in the labor market.

In the second case the tax authority ignores all informality responses. Then it would set the income tax according to the following formula

$$\frac{T_{II}'(y)}{1-T_{II}'(y)} \cdot \bar{\varepsilon}(y) \cdot y \cdot h(y) = \int_y^\infty \left[1-\bar{\lambda}(z)\right]\; dH(z). \quad (23)$$

Here, the planner effectively believes in an extreme version of the segmented market hypothesis, where the allocation of workers to the formal and the informal sectors is given and policy invariant. In this view, the tax schedule affects only the labor supply of formal workers on the intensive margin. Hence, this tax formula coincides with the formula of Diamond (1998) and Saez (2001), derived in the model with intensive margin of labor supply alone.

The following proposition compares tax rates implied by the optimal formula, denoted by T_{opt}', with the rates prescribed by the two other formulas.

Proposition 2. *Fix the distribution of formal income, the schedule of Pareto weights $\bar{\lambda}$ and the values of all other sufficient statistics required to compute the optimal tax schedule according to Theorem 1. Suppose that the status quo tax schedule has non-negative marginal tax rates and that all tax formulas prescribe a* *tax schedule which is twice differentiable. Then $T'_{opt}(y) \leq T'_I(y) \leq T'_{II}(y)$ for all y.*

We obtain a clear ordering of marginal tax rates at each income level. The optimal tax formula prescribes the lowest rates, followed by the rates set when only moonlighting is ignored, and the highest rates are chosen when all informality responses are ignored. The intuition is simple: the optimal tax formula correctly incorporates the entire fiscal cost of raising tax rates, while the other formulas miss some cost terms: the deadweight loss from jump responses of moonlighting workers and—in the case of formula I only partially—the extensive margin responses. Note that this result holds for any schedule of Pareto weights. Thus, the same ranking of tax rates holds also for the upper bound of the Pareto efficient (or, alternatively, revenue-maximizing) marginal tax rates—that case corresponds to setting $\overline{\lambda}(z) = 0$ at each positive income level. Also note that in Section 4 we conduct a similar analysis quantitatively while allowing for the endogenous adjustment of the income distribution.

3.1.2. Comparison for fixed primitives: top tax rate

Let τ be the tax rate in top bracket $[z^*, \infty)$. As a first step, let's determine how the top tax rate influences the upper tail of formal earnings. It is useful to denote the ratio of shadow and formal productivity at the top by $\phi = \lim_{\theta \to \bar{\theta}} \frac{w^s(\theta)}{w^f(\theta)}$.

Lemma 3. *Suppose that in the top bracket (i) formal productivity $w^f(\theta)$ is Pareto distributed with coefficient α, (ii) fixed cost of shadow employment κ is Pareto distributed with coefficient γ, and (iii) the Frisch elasticity of labor supply is ε. Suppose further that marginal tax rates are non-decreasing. Then the tail parameter of the formal income distribution $\alpha_y = \lim_{y \to \infty} \frac{h(y) \cdot y}{1 - H(y)}$ satisfies*

$$\alpha_y = \begin{cases} \frac{\alpha}{1+\varepsilon} & \text{if } \tau < 1 - \phi, \\ \frac{\alpha}{1+\varepsilon} + \gamma & \text{if } \tau > 1 - \phi. \end{cases} \tag{24}$$

The inverse of parameter α_y describes the *thickness* of the upper tail of the formal income distribution. When the top tax rate is sufficiently low, none of the most productive types work informally and the thickness of the formal income tail is exactly the same as in the standard Mirrlees model. As soon as the top tax rate crosses a tipping point $1 - \phi = 1 - \lim_{\theta \to \bar{\theta}} \frac{w^s(\theta)}{w^f(\theta)}$, a positive fraction of top earners joins the shadow economy. As a result, the thickness of the upper tail falls to a discretely lower value.[23] The size of this discrete fall is increasing

[23] Note that this statement does not contradict the differentiability of the aggregate tax revenue

with γ, the tail parameter of the fixed cost distribution. Intuitively, if γ is high, there are many workers with a low fixed cost of shadow employment who reduce their formal income and join the shadow economy. If instead γ is low, there are few workers with a low fixed cost of shadow employment and the formal income distribution is less affected.[24]

Now we will compare the optimal top tax rate from our model, denoted by τ^*, with the the optimal top rate in the model where the informal sector does not exist, denoted by τ_M. Since the model without the informal sector is just the standard Mirrlees model, we call τ_M a Mirrleesian top tax rate. In this comparison we take as given model primitives: the distribution of productivity and cost types, the productivity schedules and the schedule of Pareto weights, and we allow the income distribution and all other sufficient statistics to endogenously adjust to the top tax rate. To obtain analytical results, we consider the limiting top bracket as $z^* \to \infty$. The following proposition shows that the shadow economy leads to a (weakly) lower optimal top tax rate.

Proposition 3. *Suppose that the assumptions of Lemma 3 hold and that the average Pareto weight, weighted by earnings in the top bracket, is $\lambda \in [0, 1)$. Consider a sequence of top brackets $[z^*, \infty)$ such that $z^* \to \infty$ and suppose that when $\tau > 1 - \phi$, then there exists an upper bound on formal earnings of moonlighting workers that is independent of z^*. Then $\tau_M = 1 - \frac{\frac{\alpha}{1+\varepsilon}\cdot\varepsilon}{1-\lambda+\frac{\alpha}{1+\varepsilon}\cdot\varepsilon}$ for all z^* and*

$$\lim_{z^*\to\infty} \tau^* = \begin{cases} \tau_M & \text{if } \tau_M \leq 1 - \phi, \\ 1 - \phi & \text{if } \tau_M > 1 - \phi. \end{cases} \tag{25}$$

From Lemma 3 we know that setting the top tax rate above $1 - \phi$ makes the upper tail of formal earnings thinner, as many top workers join the shadow economy. In the proof of Proposition 3 we show that the resulting tax revenue loss dominates any possible redistributive gain when z^* is sufficiently high. Thus, the shadow economy effectively imposes an upper bound $1 - \phi$ on the optimal top tax rate.[25] In contrast, a top rate below $1 - \phi$ does not give incentives for informality

with respect to tax reforms, since we are discussing the impact on the shape of the income distribution in the limit as $y \to \infty$. For any finite y the ratio $\frac{h(y)\cdot y}{1-H(y)}$ is differentiable with respect to the top tax rate.

[24] Regarding the knife-edge case $\tau = 1 - \phi$, we can construct productivity schedules such that α_y takes any value between $\frac{\alpha}{1+\varepsilon}$ and $\frac{\alpha}{1+\varepsilon} + \gamma$.

[25] The assumption that formal earnings of moonlighting workers are bounded from above when $\tau > 1 - \phi$ rules out a contrived case where, as $z^* \to \infty$, the tax schedule below z^* adjusts such that $\underline{y}^f(\overline{\theta}) \to \infty$. Such scenario is not policy relevant: even if the optimal non-linear

at the top. Thus, if $\tau_M < 1 - \phi$, the optimal rate is equal τ_M.

Piketty et al. (2014) study the optimal top tax rate with income shifting on the intensive margin only, when the shifted income is taxed with exogenous tax rate t. Setting $t = 0$, their income shifting is equivalent to informality. They show that in this case the shifting responses affect the optimal top tax rate only by increasing the elasticity of reported (formal) income. Our result, derived in a somewhat different environment with intensive and extensive margin informality responses, is similar in flavor.[26] Namely, when $\tau < 1 - \phi$, then there are no informality responses and the elasticity of formal income is as in the standard Mirrlees model. On the other hand, when τ increases above $1 - \phi$, top workers start joining the informal sector, which drastically increases the elasticity of formal income and renders such tax increase suboptimal.

4. Quantitative analysis

In this section we explore the quantitative importance of our theoretical results. We estimate the model with data from Colombia and analyze the impact of informality responses on the the optimal tax schedule.

4.1. Estimation

We estimate the model using the household survey from Colombia which allows us to identify the sector and hourly wage at the main job. We restrict attention to individuals aged 24–50 years without children (34,000 observations), since they face a tax and transfer schedule which does not depend on choices absent from our modeling framework, such as assets, the number of children or college attainment. Below we explain how we identify informality in the data and introduce our estimation strategy. Further details are provided in Appendix D.

Identifying informality. We identify the main job of a given worker as informal if the worker reports not contributing to the mandatory social insurance programs. Since the social insurance contributions are paid jointly with payroll taxes

tax schedule had top tax rate above $1 - \phi$, its marginal tax rate would cross $1 - \phi$ at some finite earnings level, providing at upper bound for $\underline{y}^f$.

[26] In Piketty et al. (2014), the monetary cost of shifting income x is $d(x)$, which is an increasing and convex function satisfying $d'(0) = 0$. As a result, whenever $\tau > 0$, all agents misreport a positive share of income. In our model the monetary cost of misreporting income by x can be expressed as $\kappa + (1 - \frac{w^s(\theta)}{w^f(\theta)})x$. Thus, agents misreport income only when the tax rate is sufficiently high (i.e. when $\tau > 1 - \frac{w^s(\theta)}{w^f(\theta)}$) and, if they misreport, they do it to such extent that they leave the top tax bracket entirely.

and the withheld part of the personal income tax, a worker who pays contributions is automatically subject to income taxation. Thus, this approach is particularly well suited for our exercise.[27] We find that 58% of all workers in Colombia in 2013 were employed informally at the main job, a result consistent with other indicators of informality in Colombia.[28] The average wage in the informal sector is about half of the average wage in the formal sector and the distributions of wages in the two sectors overlap significantly. Out of workers with a formal main job about 6% have a secondary job. Some of them could be moonlighting in the shadow economy. However, the available data does not allow us to identify the sector of work in the second job.[29] Hence, we treat the informality status of the second job as a latent variable.

Estimation strategy. Using only the information on wages and sector of work does not allow us to identify the model unless we impose additional restrictions on the distribution of types (θ, κ) and productivity schedules. The reason is that any observed wage distribution and sector allocation can be an equilibrium outcome of the model in which formal and shadow productivities are equal for all workers and all the sorting is driven by the fixed cost of informal employment κ.[30]

Our identification approach is based on the assumption that productivities are log-normal conditional on observable characteristics of workers.[31] Specifically, we map sectoral log productivities of individual i to her observable characteristics X_i as follows

$$\log(w_i^f) = \log(w_0^f) + \gamma^f \cdot (X_i\beta + \epsilon_i)\,, \tag{26}$$

$$\log(w_i^s) = \log(w_0^s) + \gamma^s \cdot (X_i\beta + \epsilon_i)\,, \tag{27}$$

[27] Detecting informality via social security contributions is broadly consistent with the methodology of the International Labour Organization (ILO 2013) and is used by the Ministry of Labor of Colombia (ILO 2014), as well as by Goldberg and Pavcnik (2003), Guataquí et al. (2010) and Mora and Muro (2017) in the studies of Colombia.

[28] The official statistical agency of Colombia (DANE) follows an alternative measure of informality based on size of the establishment, status in employment and educational level of workers. They find that 57.3% and 56.7% of workers were informal in the first two quarters of 2013 (ILO 2014), which is very close to 58% we find for the entire 2013.

[29] The only information we have about the second job is the number of hours worked in the week prior to the survey, the income from that job in the month prior to the survey and if the worker is an employee or a self-account worker. There is no information on the social security payments tied to this job.

[30] Suppose that, in the data, hourly wages (from the two sectors jointly) have cumulative density F_w and share $x(w)$ of workers with hourly wage w is informal. Then set $w^f(\theta) = w^s(\theta) = \theta$, $F(\theta) = F_w(\theta)$ and $G_\theta(\tilde{\kappa}(\theta)) = x(\theta)$ to match the observed distributions exactly.

[31] This assumption was made by Magnac (1991) in the study of the Colombian informal sector, although he does not restrict the productivity type to be one-dimensional.

where β is a vector of parameters and ϵ_i is a normally distributed error term.[32] In those equations $X_i\beta + \epsilon_i$ is the empirical counterpart of the productivity type θ in the model. Parameters γ^f and γ^s allow for different slopes of the sectoral productivity schedules, while w_0^f and w_0^s control the levels.[33] This log-linear specification coincides with the commonly used Mincerian regressions (Heckman et al. 2006).

We cannot estimate the above equations directly as we would face a clear selection problem. Furthermore, we also need to estimate the distribution of the fixed cost κ. Thus, we carry on a structural estimation of the model. First, we assume that the fixed cost of informal employment κ follows a Generalized Pareto distribution with the productivity-dependent scale parameter $\sigma_\kappa \left(w^f(\theta) - w_\kappa\right)^{\alpha_\kappa}$, where σ_κ, w_κ and α_κ are parameters to be estimated. When $\alpha_\kappa = 0$, the distribution of κ is independent of the productivity type θ. Second, we specify that disutility from labor is given by $v(n) = \Gamma \frac{n^{1+1/\varepsilon}}{1+1/\varepsilon}$ with intensive margin elasticity ε equal 0.33 following Chetty (2012).

The observed log hourly wage $\mathcal{W}$ and the indicator of having a formal main job I^f for an individual with characteristics X are then drawn according to

$$\left(\mathcal{W}, I^f\right) = \begin{cases} (\log(w_0^f) + \gamma^f \cdot \theta + u, 1) & \text{with prob. } 1 - G_\theta(\tilde{\kappa}(\theta)), \\ (\log(w_0^s) + \gamma^s \cdot \theta + u, 0) & \text{with prob. } G_\theta(\tilde{\kappa}(\theta)), \end{cases} \tag{28}$$

where the productivity type is given by $\theta = X\beta + \epsilon$ with $\epsilon \sim N(0, \sigma_\epsilon^2)$, $u \sim N(0, \sigma_u^2)$ is a measurement error, $\tilde{\kappa}(\theta)$ is the formality threshold above which the worker is formal and $G_\theta(\kappa)$ is the cdf of fixed cost κ. We complement this specification with a Pareto tail for the top 1% of wages. We estimate the parameters by maximum likelihood.

Our estimation approach is closely related to the more general estimation of Roy models (Heckman and Honore 1990, French and Taber 2011). In these models the distribution of sectoral productivities is two-dimensional. In contrast, in our model the two dimensions of heterogeneity are given by productivity type θ and fixed cost of informal employment κ, where, importantly, the two can be correlated. As opposed to the identification approach proposed for Roy models, where observables

[32] Vector X contains typical regressors from Mincerian wage equations such as age, gender, education level and experience. Following Pratap and Quintin (2006), who emphasize the importance of the establishment size to explain the differences of average wages across the formal and the informal sectors, we also include job and firm characteristics such as the task performed by the worker and the size of the firm. For the full list of regressors see Appendix D.

[33] We impose that β and ϵ_i are identical in the two equations to remain consistent with the assumption that the underlying productivity type θ is one-dimensional.

are used to obtain exclusion restrictions, here we use the observable characteristics of workers to pin down the distribution of the productivity type θ. Consequently, the unconditional distribution of θ depends on the distribution of characteristics in the population.

As we discussed above, moonlighting cannot be recovered from the survey directly. We do not impose, however, that workers with a formal main job are exclusively formal. Instead, we treat the moonlighting margin as an unobservable in the estimation of the model. The estimated model will then imply moonlighting behavior which is consistent with the observed data on hourly wages and sector of the main job.

Estimation results. The left panel of Figure 4 presents the estimated productivity profiles and the density of productivity types. The bottom 25% of workers are more productive in the shadow sector while the median worker is 6% more productive formally. We find that the comparative advantage in shadow labor decreases with the productivity type.[34] Thus, as assumed in the theoretical analysis, the single-crossing condition holds. The right panel of Figure 4 compares the fraction of workers with a formal main job by quintiles of hourly wages in the data and in the estimated model. The empirical share of workers with a formal main job increases sharply with hourly wage. The model tracks the data well, showing that our parametric specification is compatible with the observed sorting of workers across sectors. The model also predicts that no workers are moonlighting. That's intuitively consistent with our theoretical findings linking tax progressivity and moonlighting (recall Proposition 1), since the empirical tax and transfer schedule in Colombia is only weakly progressive.[35] In the quantitative analysis we show that moonlighting emerges and becomes important for the optimal policy once the tax progressivity is more pronounced.

In our sample of focus and in our model, 44% of agents work informally. To understand how the model matches the empirical extent of informality, consider two counterfactual exercises. First, let's set the fixed cost of informal employment κ to zero for all agents. In this case the share of informal workers increases to 65%. The fixed cost effectively prevents many middle class workers from joining the informal sector. Second, we keep the fixed cost distribution as estimated but remove all tax distortions by replacing the empirical tax schedule with a lump-

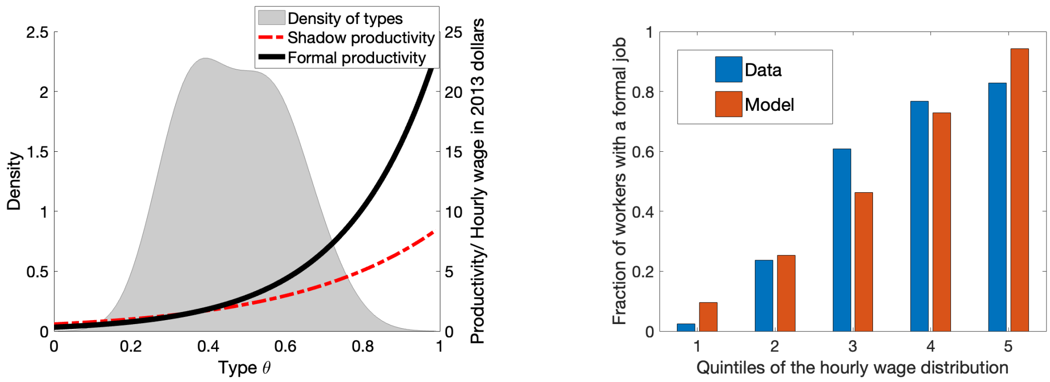
[34]Given our assumptions, $w^s(\theta)/w^f(\theta)$ is strictly decreasing when $\gamma^s - \rho^f < 0$. The point estimate of $\gamma^s - \gamma^f$ is -1.74 with a standard error of 0.08.

[35]The Colombian tax and transfer schedule is regressive at low income levels (due to phasing-out of benefits) and the progressivity at higher levels is limited, with the marginal tax rates below 38% for all but highest earners.

sum tax. Our model then implies that the share of informal workers falls to 25%. Thus, tax distortions explain a bit less than a half of the size of the Colombian shadow economy. The remaining part is explained by the fact that workers from the bottom productivity quartile are more productive informally and face low fixed cost of informal employment.[36]

Figure 4: Estimation results

(a) Productivity profiles and type distribution (b) Formality and hourly wages



Note: The productivity type distribution in panel (a) is obtained as a kernel density estimate of the distribution of $X\beta$ in the sample.

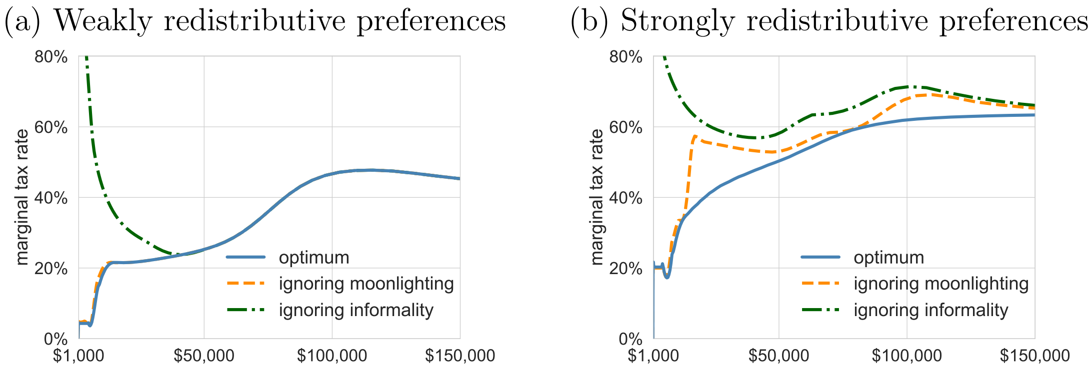
4.2. Optimal tax schedule and the role of the informal sector

In this subsection we derive the optimal tax schedules for Colombia. We then compare them to benchmark tax schedules obtained when various informality responses are ignored due to misspecified beliefs of the planner. We consider two cases of misspecified beliefs, as in Proposition 2. In the first case the planner ignores moonlighting but acknowledges the mobility of workers between sectors. In the second case the planner ignores all informality responses: both the moonlighting and the mobility between the two sectors. The latter case can be interpreted as a belief in an extreme version of the segmented market hypothesis, where the allocation of workers between the sectors of work is immutable. As we explained next to Proposition 2, the tax schedules chosen under these two cases of misspecified beliefs coincide with well-known formulas from the optimal tax literature.[37] Im-

[36] That's broadly consistent with evidence from Pratap and Quintin (2006), who show that low productivity Argentinian workers earn a higher hourly wage in the informal sector.

[37] Ignoring only moonlighting responses means that the planner follows the tax formula from Saez (2002) and Jacquet et al. (2013), while ignoring all informality responses implies the formula from Diamond (1998) and Saez (2001).

Figure 5: Equilibrium tax schedules



Note: In the optimum with weakly (strongly) redistributive social preferences the 50th, 95th and 99th percentiles of formal income are approx. $\$10,500$ ($\$9,400$), $\$45,000$ ($\$40,000$) and $\$87,000$ ($\$78,000$), respectively.

portantly, we allow the income distribution to endogenously adjust to the chosen tax schedule.

The tax schedules we present for the two benchmark cases follow the notion of the Self-confirming Policy Equilibrium (SCPE), developed by Rothschild and Scheuer (2016). Since the distribution of income is endogenous to tax policy, we find the tax schedules implied by each formula iteratively: a tax schedule implies an income distribution which, together with a tax formula, results in a new tax schedule. A SCPE is a fixed point of this mapping. In such equilibrium, the income distribution and the tax schedule are consistent with the beliefs of the planner. The planner has no incentives to adjust the policy and does not discover its misperceptions, which in our case correspond to unawareness of various informality responses. In principle, each tax formula can admit multiple SCPE. We report the equilibrium which yields the highest welfare. Each tax schedule is required to generate the same revenue as the actual Colombian income tax.

We assume that Pareto weights follow $\lambda(\theta) = r(1 - F(\theta))^{r-1}$ as in Rothschild and Scheuer (2013). The parameter $r \geq 1$ captures the strength of redistributive preferences and is equal to the Pareto weight placed on the least productive agents. The average weight is always equal to 1 and the weight of the most productive agents converges to 0 when $r > 1$. We consider two cases of social preferences: $r = 1.1$ and $r = 1.7$, which we call weakly and strongly redistributive, respectively. The Pareto weight placed on the 90th percentile of θ is approximately 0.9 for the weakly redistributive and 0.3 for strongly redistributive social preferences.

Figure 5 depicts the optimal tax schedules and the tax schedules chosen when

Table 1: Allocation of workers between sectors and welfare loss

	share of workers by sector of work			**welfare loss**
	only formal	moonlighting	only informal	(rel. to optimum, % of cons.)
Weakly redistributive preferences				
optimum	70.8%	1.4%	27.8%	
ignoring moonlighting	70.1%	2.1%	27.8%	0%
ignoring informality	32.6%	0%	67.4%	13.5%
Strongly redistributive preferences				
optimum	57.4%	3.4%	39.2%	
ignoring moonlighting	52.6%	7.6%	39.9 %	2.4%
ignoring informality	23.6%	0%	76.4%	24.8%

either moonlighting responses or all informality responses are ignored and Table 1 shows the implied distributions of workers between the sectors. Remarkably, the order of tax rates predicted by Proposition 2 continues to hold, even though the assumption of identical income distributions is clearly not satisfied. We find that ignoring all informality responses leads to higher tax rates at each income level than ignoring only moonlighting responses, while the optimal tax rates are the lowest.

The optimal tax schedules are close to fully progressive: the marginal tax rates almost always increase with income. At low income levels tax rates are low and roughly constant, they start to rise close to the median income (approx. $10,000) and stabilize at the top. A stronger taste for redistribution shifts the schedule up while roughly preserving this shape. Thus, the optimal fraction of workers with exclusively formal employment decreases with the strength of redistributive preferences from 71% to 57%. The bulk of the remaining workers are employed exclusively informally. The share of moonlighting individuals is small and increases from 1.4% to 3.4% as redistributive preferences become stronger.

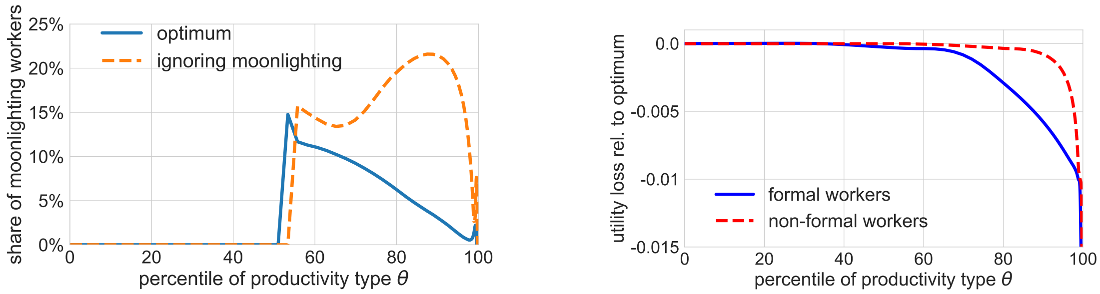
When all informality responses are ignored, the tax schedules feature very high marginal tax rates at low income levels, approaching 100% at the bottom. The tax rates are decreasing through the most of the income distribution and increase again as they approach the top income tail, generating a familiar U-shape (Diamond 1998; Saez 2001). High tax rates push most of the low and medium productivity workers to the shadow sector. Nevertheless, from the planner's perspective the tax schedule seems optimal. That's because the implied density of formal income at low and medium income levels—and, hence, the perceived deadweight loss from taxation—is, in fact, low. We find that ignoring all informality responses when setting the tax policy effectively doubles the share of shadow workers relative to the optimum. Although taxes rates are on average higher than in the optimum, tax progressivity is actually lower, since tax rates increase the most at low earnings. Consistently with our theoretical findings linking progressivity and moonlighting, the share of moonlighting workers falls relative to the optimum: virtually all shadow workers are exclusively informal. The welfare loss from ignoring all informality responses is catastrophic and ranges from 13.5% to 24.8% of consumption depending on the social welfare function, as reported in Table 1. In other words, accounting for informality brings a huge welfare gain.

When we compare the optimal tax schedule with the tax schedule when only the moonlighting responses are ignored, it is clear that the impact of moonlighting depends crucially on redistributive preferences. When preferences for redistribution are strong, the moonlighting responses reduce the marginal tax rates above the median formal income by up to 20 p.p. The moonlighting responses—complementing formal income with additional informal earnings—are important higher in the income distribution compared to the responses of switching from entirely formal to entirely informal employment. Intuitively, a secondary informal job is tempting for workers with well-paid formal jobs who face high marginal tax rates and for whom transitioning to entirely informal employment is too costly. On the other hand, when preferences for redistribution are weak, the moonlighting responses have little effect on the optimal tax schedule. That is because the tax rates for highly productive workers are not substantial enough to create incentives for informality.

When the preferences for redistribution are strong, ignoring moonlighting results in a share of moonlighting workers that more than doubles the optimal value, with a large welfare loss equivalent to 2.4% drop in consumption. Since the the tax schedule is excessively progressive, with the tax rates too high above median formal income but approximately optimal below, we should expect moonlighting to become more prevalent. However, why is the increased moonlighting so damaging for social welfare? We find that the sorting of workers across sectors is substantially different in comparison to the optimal allocation (see Figure 6, panel a). Relative to the optimum, moonlighting is induced among workers with higher productivity, mostly from the top quartile of the productivity distribution. The median percentile of productivity type of moonlighting workers increases from 66% at the optimum to 78%. As the most productive workers who face high marginal tax rates replace a fraction of their formal earnings with shadow earnings, the tax revenue is eroded heavily. In fact, although the overall level of taxes is substan-

Figure 6: Consequences of ignoring moonlighting

(a) Incidence of moonlighting (b) Utility loss from ignoring moonlighting



tially higher at high income levels when moonlighting is ignored relative to the optimum (e.g. the average tax rate at the 95th percentile of the formal earnings is higher by 8 p.p.), the overall tax revenue is actually slightly lower. It means that the least productive workers receive a lower transfer. Since the tax schedule chosen when the moonlighting responses are ignored generates a lower tax revenue while imposing higher distortions, it is Pareto inefficient. Indeed, all agents in the economy loose relative to the optimum, although losses are concentrated among the most productive workers (see Figure 6, panel b).

5. Conclusions

This paper studies the optimal income taxation when agents can earn income in a shadow economy which is unobserved by the government. The key technical contribution is allowing for workers to supply labor simultaneously to the formal and the informal sectors, which we call moonlighting. We show theoretically and quantitatively that the optimal tax schedule which accounts for informality responses features lower tax rates throughout the income distribution. In particular, the possibility of workers to migrate to entirely informal employment restricts tax rates at low and medium income levels, while the possibility of moonlighting is relevant at higher levels of income.

Theoretical tools we developed could be used in other settings. Our tax formula applies when agents can simultaneously work in two, broadly understood, sectors and the tax schedule can be optimized over the income from only one of the sectors. Examples of such settings include the model of home production or the problem of a local tax authority with residents who can work partly outside its jurisdiction.

A. Proofs from Section 2 and Section 3

Proof of Lemma 1. The strict *Spence-Mirrlees* single crossing condition holds if, keeping the formal income level fixed, the marginal rate of substitution $\frac{v'(n)}{w^f(\theta)}$ is strictly decreasing with θ, where n is the total labor supply. For formal workers it follows from the strict convexity of v. For workers that supply labor to the informal sector we have $v'(n) = w^s(\theta)$ and the single-crossing follows from $\frac{w^s(\theta)}{w^f(\theta)}$ being strictly decreasing. Given the single-crossing condition, the formal earnings schedule is increasing by Theorem 7.2 in Fudenberg and Tirole (1991). □

Proof of Proposition 1. The second-order condition of the moonlighting θ-worker is $-T''(\underline{y}^f(\theta)) \leq 0$. It cannot be satisfied if $T''(\underline{y}^f(\theta)) < 0$. If the second-order condition holds as equality, then the marginal tax rate is locally constant and the agent is indifferent between $\underline{y}^f(\theta)$ and $\underline{y}^f(\theta) + e$ for sufficiently small $e > 0$. By Assumption 2 the indifferent agent chooses higher formal earnings. Thus, the moonlighting workers never choose formal earnings where the second-order condition holds as equality. □

Lemma A.1. *The following statements hold: (1) The second-order condition with respect to formal earnings holds as a strict inequality for all workers. (2) All formal workers have a unique utility-maximizing formal earnings level conditional on remaining formal. (3) All workers with type $\theta > \underline{\theta}$, where $\underline{y}^f(\theta)$ is continuous, have a unique utility-maximizing formal earnings level conditional on earning some informal income.*

Proof of Lemma A.1. (1) The proof of Proposition 1 shows that for moonlighting workers, it is straightforward to extend the argument to the formal workers. (2) Given Assumption 3, we need to check it only for $\theta > \underline{\theta}$. Suppose on the contrary that a formal $\theta-$worker is indifferent between $\overline{y}^f(\theta)$ and strictly lower earnings y'. By continuity, there is a formal worker with productivity type $\theta' < \theta$ such that $\overline{y}^f(\theta) > \overline{y}^f(\theta') > y'$. Thus, there exists a possible equilibrium in which $\theta-$worker chooses earnings y' and the earnings choices are not increasing in θ, which contradicts Lemma 1. Note that such equilibrium is ruled out by Assumption 2, but Lemma 1 does not depend on this assumption. (3) The proof is analogous to that of statement (2) for the formal workers. □

Proof of Lemma 2. We will prove the simple case first and then generalize. Suppose that the original tax schedule is strictly progressive ($T''(y) > 0$) apart from the regressivity interval $[y_1, y_2]$. Consequently, the formal earnings schedule of moonlighting workers $\underline{y}^f(\cdot)$ is discontinuous at some θ_d, with $\underline{y}^f(\theta_d^-) < y_1$ and $\underline{y}^f(\theta_d) > y_2$. Furthermore, assume that the moonlighting $\underline{\theta}-$worker has a unique utility-maximizing choice of formal earnings. Fix direction of the reform $\mathrm{d}T \in \mathcal{C}^2$ and denote by μ the size of the reform.

First we will show that $\overline{y}^f(\theta), \underline{y}^f(\theta)$ and θ_d are continuously differentiable (denoted 'c.d.') with μ at $\mu = 0$ for almost all θ. Second, we show that almost everywhere $\tilde{\kappa}(\theta)$ is either c.d. with μ or it does not affects tax revenue to the first order. Then we will show that it implies the existence of $\mathrm{d}\mathcal{TR}$.

The first-order condition for $\overline{y}^f(\theta)$ at the reformed tax schedule $T + \mu \cdot \mathrm{d}T$ is

$$H_1(\overline{y}^f(\theta), \mu) \equiv \Big(1 - T'(\overline{y}^f(\theta)) - \mu \cdot \mathrm{d}T'(\overline{y}^f(\theta))\Big) \cdot w^f(\theta) - v'\left(\frac{\overline{y}^f(\theta)}{w^f(\theta)}\right) = 0. \quad (29)$$

By Lemma A.1 the utility-maximizing earnings level is unique which means that this equation is sufficient to pin down the equilibrium earnings level following a reform for μ small enough. Furthermore, the second-order condition holds as a strict inequality: $\frac{\partial H_1(\overline{y}^f(\theta),\mu)}{\partial \overline{y}^f(\theta)} < 0$. We can apply the implicit function theorem (IFT) which implies that $\frac{\partial y^f(\theta)}{\partial \mu} |_{\mu=0} = \mathrm{d}y^f(\theta)[T, \mathrm{d}T]$ exists and is continuous.[38] In the analogous way we can show that $\underline{y}^f(\theta)$ is c.d. with μ in the intervals $(\underline{\theta}, \theta_d)$ and $(\theta_d, \overline{\theta})$.

Now we will show that θ_d is c.d. with μ. Denote auxiliary formal income intervals $I_1 = [0, \underline{y}^f(\theta_d^-) + \epsilon]$ and $I_2 = [\underline{y}^f(\theta_d) - \epsilon, \infty)$ for small $\epsilon > 0$. Define auxiliary earnings schedules

$$\underline{y}_j^f(\theta, \mu) \equiv \arg\max_{y^f \in I_j} \left\{ \max_{y^s \geq 0} R(y^f) - \mu \cdot \mathrm{d}T(y^f) + y^s - v\left(\frac{y^f}{w^f(\theta)} + \frac{y^s}{w^s(\theta)}\right) \right\} \quad (30)$$

for all θ and $j \in \{1, 2\}$. In words, $\underline{y}_i^f(\theta, \mu)$ is the utility-maximizing formal earnings choice of a moonlighting $\theta-$worker following a tax reform of size μ when the choice is confined to I_j. Note that $\underline{y}_i^f(\theta, \mu)$ is c.d. with θ and μ. We can now write the indifference condition (8) as

$$H_2(\theta_d, \mu) \equiv T(\underline{y}_2^f(\theta_d, \mu)) - T(\underline{y}_1^f(\theta_d, \mu)) + \mu \cdot \Big(\mathrm{d}T(\underline{y}_2^f(\theta_d, \mu)) - \mathrm{d}T(\underline{y}_1^f(\theta_d, \mu))\Big)$$
$$- \Big(T'(\underline{y}_1^f(\theta_d, \mu)) + \mu \cdot \mathrm{d}T'(\underline{y}_1^f(\theta_d, \mu))\Big) \cdot \Big(\underline{y}_2^f(\theta_d, \mu) - \underline{y}_1^f(\theta_d, \mu)\Big) = 0. \quad (31)$$

Notice that $\frac{\partial H_2}{\partial \theta_d} |_{\mu=0} = -T''(\underline{y}_1^f(\theta_d, 0)) \cdot \frac{d\underline{y}_1^f(\theta_d, 0)}{d\theta_d} \cdot \Big(\underline{y}_2^f(\theta_d, 0) - \underline{y}_1^f(\theta_d, 0)\Big)$ is negative:

[38] See for instance de Oliveira (2014), Theorem 5.

$T'' > 0$ holds for moonlighting workers and the continuity of T' implies that $\frac{\partial \underline{y}_1^f(\theta_d,0)}{\partial \theta_d} > 0$. Then by IFT θ_d is c.d. with μ.

Regarding threshold $\tilde{\kappa}(\theta)$, it is straightforward to show that it is c.d. with μ when $\tilde{\kappa}(\theta) > 0$ by applying IFT to equation (2). However, $\tilde{\kappa}(\theta)$ can be non-differentiable with μ when $\tilde{\kappa}(\theta) = 0$, as it cannot decrease below 0. It would be problematic if for a positive measure of productivity types we had $\overline{y}^f(\theta) = \underline{y}^f(\theta) > \underline{y}^f(\theta^-)$ and $\tilde{\kappa}(\theta) = 0$ (in words: $(\theta, 0)$-worker is indifferent between two formal income levels, the lower of which involves informal activity), since then a movement of these workers to informality would have a first-order impact on tax revenue.[39] Below we show that in such cases the expected utility $V(\theta, 0)$ is non-differentiable with respect to the productivity type. Since $V(\cdot, 0)$ has a measure zero of non-differentability points by Milgrom and Segal (2002) (Corollary 1 and footnote 10), there is a measure zero of such cases and they do not affect the behavior of $\mathcal{TR}$. To show that $V(\cdot, 0)$ is not differentiable at θ, denote $\overline{n}^f = \frac{\overline{y}^f(\theta)}{w^f(\theta)}$, $\underline{n}^f = \frac{\underline{y}^f(\theta^-)}{w^f(\theta)}$ and $n^m = v'^{-1}(w^s(\theta))$. The directional derivatives of $V(\theta, 0)$ are $V_\theta(\theta^-, 0) = \left(\frac{\dot{w}^f(\theta)}{w^f\theta}\underline{n}^f + \frac{\dot{w}^s(\theta)}{w^s\theta}(n^m - \underline{n}^f)\right) v'(n^m)$ and $V_\theta(\theta^+, 0) = \frac{\dot{w}^f(\theta)}{w^f\theta}\overline{n}^f v'(\overline{n}^f)$, where $\dot{w}^i \equiv \frac{dw^i(\theta)}{d\theta}$. We have $V_\theta(\theta^+, 0) > V_\theta(\theta^-, 0)$ when

$$\frac{\dot{w}^f(\theta)}{w^f(\theta)}\left(\overline{n}^f v'(\overline{n}^f) - \underline{n}^f v'(n^m)\right) > \frac{\dot{w}^s(\theta)}{w^s(\theta)}\left(n^m v'(n^m) - \underline{n}^f v'(n^m)\right). \tag{32}$$

By Assumption 1 $\frac{\dot{w}^f(\theta)}{w^f(\theta)} > \frac{\dot{w}^s(\theta)}{w^s(\theta)}$. We also have $\overline{n}^f \geq n^m$, since otherwise $w^s(\theta) > (1 - T'(\overline{y}^f(\theta))w^f(\theta)$ and type $(\theta, 0)$ would be strictly better off moonlighting than staying formal, which contradicts $\tilde{\kappa}(\theta) = 0$. Thus, the above inequality holds.

Now we will apply Leibniz integral rule.[40] Write the tax revenue as

$$\mathcal{TR} = \int_{\underline{\theta}}^{\overline{\theta}} T(\overline{y}^f(\theta)) \cdot (1 - G_\theta(\tilde{\kappa}(\theta)))dF(\theta)$$
$$+ \int_{\underline{\theta}}^{\theta_d} T(\underline{y}_1^f(\theta)) \cdot G_\theta(\tilde{\kappa}(\theta))dF(\theta) + \int_{\theta_d}^{\overline{\theta}} T(\underline{y}_2^f(\theta)) \cdot G_\theta(\tilde{\kappa}(\theta))dF(\theta). \tag{33}$$

Since for each integral on the right-hand side the integrand as well as the edges of

[39] One can construct an economy in which a positive measure of productivity types has $\tilde{\kappa}(\theta) = 0$ and is indifferent between staying formal or joining the shadow economy, but conditional on joining the shadow economy they would choose formal incomes in the neighborhood of their original earnings, implying that the overall impact on tax revenue is zero to the first order. E.g. suppose that $1 - T'(\overline{y}^f(\theta)) = \frac{w^s(\theta)}{w^f(\theta)}$ for all θ, such that for all types we have $\tilde{\kappa}(\theta) = 0$ and $\overline{y}^f(\theta) = \underline{y}^f(\theta) = \underline{y}^f(\theta^-)$. Increasing marginal tax rates uniformly increases informality, but this increase of informality has no first-order impact on tax revenue.

[40] See Theorem 2.4.1 in Casella and Berger (2002).

the integrating region are either constant or c.d. with μ at $\mu = 0$, the derivative of each integral with μ at $\mu = 0$ exists. Thus, the derivative of the left-hand side exists and we denote it by $\mathrm{d}\mathcal{TR}[T, \mathrm{d}T]$.

Below we describe how to generalise this result to more complex cases:

1. Multiple discontinuities. Since $\underline{y}^f$ is increasing, it has countably many discontinuity points $\{\theta_{d1}, \theta_{d2}, ...\}$. For each discontinuity point we need to keep track of two auxiliary intervals: the ones containing the highest and the second-highest utility-maximizing formal earnings level. Define countably many income intervals $I_1, I_2, ..., I_i, ...$ in the following way: $I_1 = [0, \underline{y}^f(\theta_{d1})+\epsilon]$, $I_2 = [\underline{y}^f(\theta_{d1})-\epsilon, \underline{y}^f(\theta_{d2})+\epsilon]$, $I_i = [\underline{y}^f(\theta_{di-1}) - \epsilon, \underline{y}^f(\theta_{di}) + \epsilon]$ and so on for small $\epsilon > 0$. For each I_i define the auxiliary earnings schedule $\underline{y}^f_i(\theta, \mu)$ as in (30). Following the steps from the simple case, it is easy to show that each θ_{di} is c.d. with μ at $\mu = 0$. Thus, we can write $\mathcal{TR}$ as a sum of countably many integrals, each with the integrand and the edges of the integration region which are c.d. with μ at $\mu = 0$. By Leibniz integral rule, $\mathrm{d}\mathcal{TR}$ exists.

2. Non-unique utility-maximizing choice for moonlighting $\underline{\theta}$−worker. Treat $\underline{\theta}$ as a discontinuity point and apply the case of multiple discontinuities above. □

Proof of Theorem 1. Integrating by parts, the welfare effect from (12) becomes

$$WE \quad = - \left[\mathrm{d}T(y) \int_0^y \bar{\lambda}(z)h(z)dz\right]_{y=0}^{y\to\infty} + \int_0^\infty \mathrm{d}T'(y) \int_0^y \bar{\lambda}(z)h(z)dzdy. \tag{34}$$

Recall that the average Pareto weight $\int_0^\infty \bar{\lambda}(z)h(z)dz$ is 1. Then the first term is $-\lim_{y\to\infty} \mathrm{d}T(y) = -\int_0^\infty \mathrm{d}T'(y)dy$. Rearranging, we arrive at

$$WE = -\int_0^\infty \left[\int_y^\infty \bar{\lambda}(z)h(z)dz\right] \mathrm{d}T'(y)dy. \tag{35}$$

Analogously, we can express mechanical effect ME as $\int_0^\infty \left[(1 - H(y)\right] \mathrm{d}T'(y)dy$.

Using $\overline{s}(y)$, defined explicitly in the statement of the theorem, the behavioral effect due to intensive responses BE_{int} can be written as

$$-\int_0^\infty \left[\frac{T'(y)}{1-T'(y)}\tilde{\varepsilon}^f(y)yh^f(y) + \frac{T'(\overline{s}(y))}{1+T'(\overline{s}(y))}\tilde{\varepsilon}^s(\overline{s}(y))\overline{s}(y)h^s(\overline{s}(y))\right] \mathrm{d}T'(y)dy.$$

$\overline{s}(y)$ stands for the formal income level at which the moonlighting workers respond on the intensive margin to the reform: $\overline{s}(y) = y$ if the earning schedule of moonlighting workers is locally continuous and $\overline{s}(y) > y$ otherwise. If there are no moonlighting workers with earnings $\geq y$, then there are no intensive margin responses of moonlighting workers, $\overline{s}(y) = 0$ and the second term in the right-hand side disappears.

Write behavioral effect due to extensive responses (19) as

$$BE_{ext} = -\int_0^\infty \Delta T(z)\pi(z)h^f(z)\int_0^\infty \mathbb{1}(\rho(z) \leq y \leq z)\,\mathrm{d}T'(y)dydz \tag{36}$$
$$= -\int_0^\infty \left[\int_y^\infty \Delta T(z)\pi(z)h^f(z)\mathbb{1}(\rho(z) \leq y)dz\right]\mathrm{d}T'(y)dy, \tag{37}$$

where in the second row we exchanged the order of integration and expressed the second inequality within the identity function as a limit of the integration interval.

Plugging the terms into optimality condition (20) leads to

$$\int_0^\infty \Bigg[-\frac{T'(y)}{1-T'(y)}\tilde{\varepsilon}^f(y)yh^f(y) - \frac{T'(\overline{s}(y))}{1+T'(\overline{s}(y))}\tilde{\varepsilon}^s(\overline{s}(y))\overline{s}(y)h^s(\overline{s}(y))$$
$$+\int_y^\infty [1-\bar{\lambda}(z)]dH(z) + \int_y^\infty \Delta T(z)\pi(z)\mathbb{1}(\rho(z) \leq y)dH^f(z)\Bigg]\,\mathrm{d}T'(y)dy = 0, \tag{38}$$

which holds for an arbitrary reform iff formula (21) holds for all y. □

Proof of Proposition 2. Note that we treat the entire term $\Delta T(z) \cdot \pi(z)$, which stands for the elasticity of $h^f(z)$ with respect to $\Delta T(z)$, as fixed. Consider raising tax rate at y. Formula I does not account for the intensive margin responses of moonlighting workers when $\overline{s}(y) > y$ as well as for extensive margin responses at formal earnings z where $0 < \rho(z) \leq y$. Formula II in addition does not account for extensive responses when $\rho(z) = 0$. Since the status quo tax schedule has non-negative marginal tax rates, both intensive and extensive margin responses have a non-positive impact on the tax revenue. Thus, formulas I and II underestimate the cost of raising tax rate relative to the actual cost, and formula II underestimates it further relative to formula I. This implies the ranking of tax rates. □

Lemma A.2. *Suppose that marginal tax rates are non-decreasing, tax rate in the top bracket $[z^*, \infty)$ is $\tau \geq 1-\phi$, $\underline{y}^f$ is bounded from above by $\tilde{z}$ and Frisch elasticity in the top bracket is ε. Consider θ^* s.t. $\overline{y}^f(\theta^*) \geq z^*$. Then $\psi(\theta^*) \geq \frac{\tilde{\kappa}(\theta)}{w^f(\theta)^{1+\varepsilon}} \geq$*

$\psi_{lb}(\theta^*)$ *for all* $\theta \geq \theta^*$*, where* $\psi(\theta^*) = \frac{1}{1+\varepsilon}((\frac{w^s(\theta^*)}{w^f(\theta^*)})^{1+\varepsilon} - (1-\tau)^{1+\varepsilon})$ *and*

$$\psi_{lb}(\theta^*) = \psi(\overline{\theta}) - \left(\frac{w^s(\theta^*)}{w^f(\theta^*)} - (1-\tau)\right) \cdot \frac{\tilde{z}}{w^f(\theta^*)^{1+\varepsilon}} + (1-\tau)^{1+\varepsilon} - \frac{R(\overline{y}^f(\theta^*)) - R(\underline{y}^f(\theta^*))}{\overline{y}^f(\theta^*) - \underline{y}^f(\theta^*)} \cdot (1-\tau)^{\varepsilon}. \quad (39)$$

Proof of Lemma A.2. W.l.o.g. $v(n) = (1+\frac{1}{\varepsilon})^{-1} \cdot n^{1+\frac{1}{\varepsilon}}$. One can show that threshold $\tilde{\kappa}(\theta) = V(\theta, 0) - \lim_{\kappa\to\infty} V(\theta, \kappa)$ is equal

$$\tilde{\kappa}(\theta) = w^f(\theta)^{1+\varepsilon} \cdot \psi(\theta) - \left(\frac{w^s(\theta)}{w^f(\theta)} - \frac{R(\overline{y}^f(\theta)) - R(\underline{y}^f(\theta))}{\overline{y}^f(\theta) - \underline{y}^f(\theta)}\right) \cdot \underline{y}^f(\theta) \quad (40)$$

$$+ ((1-\tau) \cdot w^f(\theta))^{1+\varepsilon} - \frac{R(\overline{y}^f(\theta)) - R(\underline{y}^f(\theta))}{\overline{y}^f(\theta) - \underline{y}^f(\theta)} \cdot \overline{y}^f(\theta), \quad (41)$$

where $\psi(\theta)$ is defined in the lemma. The following is true: *(i)* $\psi(\theta)$ is strictly decreasing in θ, *(ii)* $\frac{R(\overline{y}^f(\theta))-R(\underline{y}^f(\theta))}{\overline{y}^f(\theta)-\underline{y}^f(\theta)}$ is decreasing in θ because of non-decreasing marginal tax rates and it converges to $1-\tau$ as $\theta \to \overline{\theta}$, *(iii)* $\frac{w^s(\theta)}{w^f(\theta)} - \frac{R(\overline{y}^f(\theta))-R(\underline{y}^f(\theta))}{\overline{y}^f(\theta)-\underline{y}^f(\theta)} > 0$, since otherwise a moonlighting $\theta-$worker would be better-off remaining fully formal—note that formal $\theta-$workers supply less labor than the non-formal ones. It follows that the bounds from the lemma hold. □

Proof of Lemma 3. Define the local Pareto parameter at earnings y as $a(y) = \frac{h(y)\cdot y}{1-H(y)}$. When $1-\tau > \phi$, workers with sufficiently high θ are formal and we have[41]

$$\lim_{y\to\infty} a(y) = \underbrace{\lim_{\theta\to\overline{\theta}} \frac{f(\theta)\cdot w^f(\theta)}{1-F(\theta)} \cdot \left(\frac{dw^f(\theta)}{d\theta}\right)^{-1}}_{=\alpha} \cdot \underbrace{\left(\frac{d\overline{y}^f(\theta)}{dw^f(\theta)} \cdot \frac{w^f(\theta)}{\overline{y}^f(\theta)}\right)^{-1}}_{=(1+\varepsilon)^{-1} \text{ by } (4)} = \frac{\alpha}{1+\varepsilon}. \quad (42)$$

When $1-\tau < \phi$, we can use the bounds on $\frac{\tilde{\kappa}(\theta)}{w^f(\theta)^{1+\varepsilon}}$ from Lemma A.2 to bound the local Pareto parameter:

$$\frac{\psi_{lb}(\theta)^{-\gamma}}{\psi(\theta)^{-\gamma}} \frac{w^f(\theta)^{-\gamma(1+\varepsilon)} f(\theta)}{\int_\theta^{\overline{\theta}} w^f(t)^{-\gamma(1+\varepsilon)} dF(t)} \frac{\overline{y}^f(\theta)}{\frac{d\overline{y}^f(\theta)}{d\theta}} \geq a(\overline{y}^f(\theta)) \geq \frac{\psi(\theta)^{-\gamma}}{\psi_{lb}(\theta)^{-\gamma}} \frac{w^f(\theta)^{-\gamma(1+\varepsilon)} f(\theta)}{\int_\theta^{\overline{\theta}} w^f(t)^{-\gamma(1+\varepsilon)} dF(t)} \frac{\overline{y}^f(\theta)}{\frac{d\overline{y}^f(\theta)}{d\theta}}.$$

Since $\psi_{lb}(\theta) \to \psi(\overline{\theta})$ as $\theta \to \overline{\theta}$ and formal wages are Pareto distributed, both sides

[41]Formal productivity being Pareto distributed implies that $1-F(\theta) = k \cdot w^f(\theta)^{-\alpha}$ and $f(\theta) \cdot \left(\frac{dw^f(\theta)}{d\theta}\right)^{-1} = \alpha \cdot k \cdot w^f(\theta)^{-(\alpha+1)}$.

converge to $\frac{\alpha}{1+\varepsilon}+\gamma$ as $\theta \to \overline{\theta}$. $\square$

Proof of Proposition 3. For derivations of τ_M see e.g. Piketty and Saez (2013). Regarding τ^*, if $\tau_M < 1-\phi$ then all top productivity types have a strict preference for formality as $z^* \to \infty$. Thus, the Mirrleesian tax formula still applies in the model with a shadow economy for sufficiently high z^* and $\lim_{z^*\to\infty} \tau^* = \tau_M$.

Suppose that $\tau \geq 1-\phi$ and consider z^* high enough such that $\tau > 1 - \frac{w^s(\theta^*)}{w^f(\theta^*)}$, where θ^* satisfies $\overline{y}^f(\theta^*) = z^*$. Consider increasing the top tax rate marginally. The combined fiscal and welfare gain of doing so is given by

$$\Phi(\tau, z^*) = 1 - \lambda - \frac{\tau}{1-\tau} \cdot a \cdot \varepsilon - \mathbb{E}[\pi(z) \cdot \Delta T(z) \mid z \geq z^*], \tag{43}$$

where $a = \frac{\bar{z}}{\bar{z}-z^*}$ for $\bar{z}$ equal to the average earnings in the top bracket (derivations are standard and omitted). Focus on the the last term, we have

$$\pi(\overline{y}^f(\theta)) \cdot \Delta T(\overline{y}^f(\theta)) = \frac{g_\theta(\tilde{\kappa}(\theta)) \cdot \tilde{\kappa}(\theta)}{1 - G_\theta(\tilde{\kappa}(\theta))} \cdot \frac{w^f(\theta)^{1+\varepsilon}}{\tilde{\kappa}(\theta)} \cdot \frac{\Delta T(\overline{y}^f(\theta))}{w^f(\theta)^{1+\varepsilon}}. \tag{44}$$

Let's bound this term from both sides for any $\theta \geq \theta^*$. The first factor on the right-hand side is γ when $\tau > 1-\phi$ and the second can be bounded by Lemma A.2. Using the assumption of non-decreasing marginal tax rates, we can bound the third factor from above

$$\frac{\Delta T(\overline{y}^f(\theta))}{w^f(\theta)^{1+\varepsilon}} \leq \frac{\tau \cdot \overline{y}^f(\theta)}{w^f(\theta)^{1+\varepsilon}} = \tau \cdot (1-\tau)^\varepsilon \tag{45}$$

and from below

$$\frac{\Delta T(\overline{y}^f(\theta))}{w^f(\theta)^{1+\varepsilon}} = \frac{T(\overline{y}^f(\theta)) - T(\underline{y}^f(\theta))}{\overline{y}^f(\theta) - \underline{y}^f(\theta)} \left((1-\tau)^\varepsilon - \frac{\underline{y}^f(\theta)}{w^f(\theta)^{1+\varepsilon}} \right) \tag{46}$$

$$\geq \frac{T(\overline{y}^f(\theta^*)) - T(\underline{y}^f(\theta^*))}{\overline{y}^f(\theta^*) - \underline{y}^f(\theta^*)} \left((1-\tau)^\varepsilon - \frac{\tilde{z}}{w^f(\theta^*)^{1+\varepsilon}} \right). \tag{47}$$

The implied bounds on $\pi(\overline{y}^f(\theta)) \cdot \Delta T(\overline{y}^f(\theta))$ have a common limit as $\theta^* \to \overline{\theta}$, which is $\gamma \cdot \frac{(1+\varepsilon)\cdot\tau\cdot(1-\tau)^\varepsilon}{\phi^{1+\varepsilon}-(1-\tau)^{1+\varepsilon}} \equiv \xi(\tau)$. Thus, $\xi(\tau)$ is also the limit of $\mathbb{E}[\pi(z) \cdot \Delta T(z) \mid z \geq z^*]$

as $z^* \to \infty$. Note that the integral $\int_{1-\phi}^{\tau} \xi(t)dt$ is infinite for any $\tau \in (1-\phi, 1)$:

$$\int_{1-\phi}^{\tau} \xi(t)dt \geq k_1 \int_{1-\phi}^{\tau} \frac{1}{\phi^{1+\varepsilon} - (1-t)^{1+\varepsilon}} dt$$
$$= k_1 \int_0^{x(\tau)} \frac{1}{x} \left(\frac{dx}{dt}\right)^{-1} dx \geq k_2 \int_0^{x(\tau)} \frac{1}{x} dx = +\infty, \quad (48)$$

where $x(t) = \phi^{1+\varepsilon} - (1-t)^{1+\varepsilon}$, $k_1 = \gamma \cdot (1+\varepsilon) \cdot \min_{t \in [1-\phi, \tau]}\{t \cdot (1-t)^{\varepsilon}\}$ and $k_2 = \frac{k_1}{(1+\varepsilon)\cdot\phi^{\varepsilon}}$. In the limit as $z^* \to \infty$ the tax revenue loss from crossing the tipping point $1-\phi$ always dominates any redistributive gains, which are finite. Thus, when $\tau_M \geq 1-\phi$, τ^* is equal $1-\phi$ for sufficiently high z^* or converges to it from below. □

B. Detailed derivations of the impact of tax reforms

Consider an arbitrary tax reform in direction $\mathrm{d}T$ of size $\mu > 0$. Let's evaluate the first-order condition for formal workers (4) at the reformed tax schedule. Supressing the productivity type θ for brevity, we obtain

$$\left(1 - \left((T'(\overline{y}^f) + \mu \cdot \mathrm{d}T'(\overline{y}^f) + T''(\overline{y}^f) \cdot \mu \cdot \mathrm{d}\overline{y}^f\right)\right) w^f = v'\left(\frac{\overline{y}^f + \mu \cdot \mathrm{d}\overline{y}^f}{w^f}\right). \quad (49)$$

Subtract (4), divide by μ and evaluate in the limit as $\mu \to 0$ to get

$$-\mathrm{d}T'(\overline{y}^f) - T''(\overline{y}^f) \cdot \mathrm{d}\overline{y}^f = v''\left(\frac{\overline{y}^f}{w^f}\right) \cdot \frac{\mathrm{d}\overline{y}^f}{(w^f)^2}. \quad (50)$$

Substituting $\mathrm{d}\left[1 - T'(\overline{y}^f)\right]$ for $-\mathrm{d}T'(\overline{y}^f)$ and rearranging yields the earnings elasticity of formal workers

$$\tilde{\varepsilon}^f = \frac{\mathrm{d}\overline{y}^f}{\mathrm{d}\left[1 - T'(\overline{y}^f)\right]} \frac{1 - T'(\overline{y}^f)}{\overline{y}^f} = \left(\frac{1}{\varepsilon} + \frac{T''(\overline{y}^f) \cdot \overline{y}^f}{1 - T'(\overline{y}^f)}\right)^{-1} \quad (51)$$

where $\varepsilon = \frac{v'}{v''} \frac{w^f}{\overline{y}^f}$ is the Frisch elasticity, or the elasticity of earnings along the linear tax schedule.

Following analogous steps with respect to the first-order condition of the moonlighting workers (6), we obtain $-\mathrm{d}T'(\underline{y}^f) - T''(\underline{y}^f) \cdot \mathrm{d}\overline{y}^f = 0$. The term involving v''

is not present, since the total labour supply does not change. Rearranging yields

$$\tilde{\varepsilon}^s = \frac{\mathrm{d}\underline{y}^f}{\mathrm{d}\Big[1 - T'(\underline{y}^f)\Big]} \frac{1 - T'(\underline{y}^f)}{\underline{y}^f} = \frac{1 - T'(\underline{y}^f)}{T''(\underline{y}^f) \cdot \underline{y}^f}. \tag{52}$$

Suppose that $\underline{y}^f(\cdot)$ is discontinuous at some productivity type θ_d such that $\underline{y}^f(\theta_d) > \underline{y}^f(\theta_d^-)$. Denote these two earnings levels by $\overline{s}$ and $\underline{s}$. Express the indifference condition (8) as $T(\overline{s}) - T(\underline{s}) = T'(\overline{s}) \cdot (\overline{s} - \underline{s})$. Differentiating:

$$\begin{aligned} &\mathrm{d}T(\overline{s}) - \mathrm{d}T(\underline{s}) + T'(\overline{s}) \cdot \mathrm{d}\overline{s} - T'(\underline{s}) \cdot \mathrm{d}\underline{s} = \\ &\qquad \mathrm{d}T'(\overline{s}) \cdot (\overline{s} - \underline{s}) + T''(\overline{s}) \cdot \mathrm{d}\overline{s} \cdot (\overline{s} - \underline{s}) + T'(\overline{s}) \cdot (\mathrm{d}\overline{s} - \mathrm{d}\underline{s}). \end{aligned} \tag{53}$$

Note that $T'(\overline{s}) = T'(\underline{s})$, which follows from interior first-order condition (6) holding for type θ_d at both $\overline{s}$ and $\underline{s}$. Consequently, the right terms on the two sides cancel out and we get

$$\mathrm{d}\overline{s} = \frac{\mathrm{d}\big[T(\overline{s}) - T(\underline{s})\big]}{T''(\overline{s}) \cdot (\overline{s} - \underline{s})} - \frac{\mathrm{d}T'(\overline{s})}{T''(\overline{s})}. \tag{54}$$

The first term on the right-hand side captures the change of $\overline{s}$ due to moonlighting workers jumping to (or from) a discretely lower earnings $\underline{s}$ in response to change of the relative tax burden $\mathrm{d}\big[T(\overline{s}) - T(\underline{s})\big]$. The second term corresponds to the marginal response to change in the tax rate $\mathrm{d}T'(\overline{s})$. In order to isolate the jumping responses, suppose that $\mathrm{d}T'(\overline{s}) = 0$. Then we have that

$$\frac{\mathrm{d}\overline{s}}{\mathrm{d}\big[R(\overline{s}) - R(\underline{s})\big]} \frac{R(\overline{s}) - R(\underline{s})}{\overline{s}} = -\frac{1 - T'(\overline{s})}{\overline{s} \cdot T''(\overline{s})} = -\tilde{\varepsilon}^s(\overline{s}), \tag{55}$$

where $R(y) = y - T(y)$ is the formal after-tax income and we use $\big(R(\overline{s}) - R(\underline{s})\big) = (1 - T'(\overline{s})) \cdot (\overline{s} - \underline{s})$ which follows from (8). Thus, the jumping responses following the change in the relative after-tax income (or average net-of-tax rate) $\mathrm{d}\big[R(\overline{s}) - R(\underline{s})\big]$ are described by exactly the same elasticity as the marginal responses to a change of the (marginal) net-of-tax rate $\mathrm{d}\big[1 - T'(\overline{s})\big]$. The minus sign is due to the fact that $\overline{s}$ going up means that agents are jumping down—the income responses are of the opposite sign to $\mathrm{d}\overline{s}$.

Regarding the extensive margin responses, the earnings density of formal workers is equal $h^f(\overline{y}^f(\theta)) = (1 - G_\theta(\tilde{\kappa}(\theta)) \cdot f(\theta) \cdot \left(\frac{d\overline{y}(\theta)}{d\theta}\right)^{-1}$. Differentiation yields

$$\begin{aligned} &\mathrm{d}h^f(\overline{y}^f(\theta)) + h^{f\prime}(\overline{y}^f(\theta)) \cdot \mathrm{d}\overline{y}^f(\theta) \\ &\qquad = h^f(\overline{y}^f(\theta)) \cdot \left(-\frac{g_\theta(\tilde{\kappa}(\theta)) \cdot \mathrm{d}\tilde{\kappa}(\theta)}{1 - G_\theta(\tilde{\kappa}(\theta))} + \left(\frac{d\overline{y}(\theta)}{d\theta}\right) \cdot \mathrm{d}\left[\left(\frac{d\overline{y}(\theta)}{d\theta}\right)^{-1}\right]\right). \end{aligned} \tag{56}$$

We are interested in the impact of the tax reform on the earnings density through the threshold $\tilde{\kappa}(\theta)$; the other terms are related to the intensive margin responses which we already accounted for. Ignoring the intensive margin terms, we obtain (the absolute value of) the semi-elasticity of the density of formal workers with respect to the tax burden of staying formal:

$$\pi(\theta) = -\frac{\mathrm{d}h^f(\overline{y}^f(\theta))}{\mathrm{d}\left[T(\overline{y}^f(\theta) - T(\underline{y}^f(\theta))\right]} \cdot \frac{1}{h^f(\overline{y}^f(\theta))} = \frac{g_\theta(\tilde{\kappa}(\theta))}{1 - G_\theta(\tilde{\kappa}(\theta)} \cdot \frac{1}{h^f(\overline{y}^f(\theta))}, \tag{57}$$

where we used $\mathrm{d}\tilde{\kappa}(\theta) = \mathrm{d}\left[T(\overline{y}^f(\theta) - T(\underline{y}^f(\theta))\right]$, implied by (2).

While all the above elasticities are expressed as a function of the productivity type θ, we can express them equivalently as functions of formal earnings, since $\theta \mapsto \overline{y}^f(\theta)$ is strictly increasing over the entire domain and $\theta \mapsto \underline{y}^f(\theta)$ is strictly increasing when $\underline{y}^f(\theta) > 0$.

C. Two-dimensional heterogeneity in productivities

We can extend our optimal tax formula to an economy in which the distribution of formal and shadow productivities is two-dimensional. Suppose that the type is given by $(\alpha, \theta, \kappa) \in \mathcal{A} \times [\underline{\theta}, \overline{\theta}] \times [0, \infty) \subseteq \mathbb{R}^3_+$, $\mathcal{A}$ finite, such that a worker of type (α, θ, κ) has productivities $w^f_\alpha(\theta)$ and $w^s_\alpha(\theta)$. Assume that the productivity schedules satisfy Assumption 1 for each $\alpha \in \mathcal{A}$. Denote the p.d.f. of α by $A(\cdot)$, the c.d.f. of θ conditional on α by $F_\alpha(\cdot)$, and the c.d.f. of κ conditional on (α, θ) by $G_{\alpha,\theta}(\cdot)$. All cumulative density functions are assumed twice continuously differentiable. We maintain Assumption 2 and suppose that Assumption 3 holds for each α to rule out formal workers responding with jumps. In what follows, x_α denotes variable x evaluated at type α and x without a subscript indicates the average across α types. For instance, $h_\alpha(z)$ is the formal earnings density of workers with type α at earnings z, while $h(z) = \sum_{\alpha \in \mathcal{A}} h_\alpha(z) \cdot A(\alpha)$ is the overall formal earnings density at z.

Consider initial tax $T \in \mathcal{C}^2$ and a direction of a tax reform $\mathrm{d}T \in \mathcal{C}^2$. The optimal tax schedule needs to satisfy

$$\sum_{\alpha \in \mathcal{A}} \left[ME_\alpha + WE_\alpha + BE_{int,\alpha} + BE_{ext,\alpha}\right] \cdot A(\alpha) = 0. \tag{58}$$

The following theorem expresses this condition as a tax formula.

Theorem 2. *Suppose that the optimal tax schedule is twice continuously differentiable. The optimal tax rate at earnings y satisfies*

$$\frac{T'(y)}{1-T'(y)} \cdot \tilde{\varepsilon}^f(y) \cdot y \cdot h^f(y) + \sum_{s \in \overline{S}(y)} \frac{T'(s)}{1-T'(s)} \cdot \tilde{\varepsilon}^s(s) \cdot s \cdot h^s(s)$$
$$= \int_y^\infty \left[1 - \bar{\lambda}(z)\right] dH(z) - \int_y^\infty \overline{\Delta T}(z) \cdot \overline{\pi}(z,y)\; dH^f(z) \tag{59}$$

where (i) $\overline{S}(y) = \{\overline{s}_\alpha(y) : \alpha \in \mathcal{A}\}$, for $\overline{s}_\alpha(y)$ defined as $\min\{z \in Im(\underline{y}^f_\alpha) : z \geq y\}$ if min. exists and 0 otherwise, is a set of formal earnings at which moonlighting workers are responding on the intensive margin to the raise of $T'(y)$, (ii) $\overline{\Delta T}(z) = \sum_\alpha \Delta T_\alpha(z) \cdot h^f_\alpha(z) \cdot A(\alpha)$ is the average tax burden of staying formal at z and (iii) $\overline{\pi}(z,y) = \sum_{\alpha \in \mathcal{A}} \frac{\Delta T_\alpha(z)}{\overline{\Delta T}(z)} \cdot \pi_\alpha(z) \cdot \mathbb{1}(\rho_\alpha(z) \leq y) \cdot \frac{h^f_\alpha(z) \cdot A(\alpha)}{h^f(z)}$ is the average semi-elasticity of density of formal workers at earnings z with respect to $T'(y)$ weighted by the tax burden of staying formal.

Proof. Following the steps in the proof of Theorem 1, it is easy to show that optimality condition (20) holds iff at every $y > 0$ we have

$$\sum_\alpha A(\alpha)\Bigg[-\frac{T'(y)}{1-T'(y)}\tilde{\varepsilon}^f(y) y h^f_\alpha(y) - \frac{T'(\overline{s}_\alpha(y))}{1+T'(\overline{s}_\alpha(y))}\tilde{\varepsilon}^s_\alpha(\overline{s}_\alpha(y))\overline{s}_\alpha(y) h^s_\alpha(\overline{s}(y))$$
$$+ \int_y^\infty [1 - \bar{\lambda}_\alpha(z)] dH_\alpha(z) + \int_y^\infty \Delta T_\alpha(z)\pi_\alpha(z)\mathbb{1}(\rho_\alpha(z) \leq y) dH^f_\alpha(z)\Bigg] = 0, \tag{60}$$

Averaging each term within square brackets over α types separately, it is easy to express the average mechanical and welfare effects terms in the equation above as in (59). Same is true for the term capturing the intensive responses of formal workers, since all formal workers with earnings y have identical elasticity $\tilde{\varepsilon}^f(y)$.

The intensive responses of moonlighting workers can now happen at multiple earnings levels simultaneously, captured by the set $\overline{S}(y) = \{\overline{s}_\alpha(y) : \alpha \in \mathcal{A}\}$. Furthermore, for each $s \in \overline{S}(y)$ we have $h^s(s) = \sum_\alpha h^s_\alpha(s)\mathbb{1}(\overline{s}_\alpha(y) = s)A(\alpha)$, i.e. at each earnings level $s \in \overline{S}(y)$ there are only the moonlighting workers who respond on the intensive margin to a change of $T'(y)$. To shows this, suppose that there is some type (α_1, θ_1) and earnings level $y > 0$ for which $\underline{y}^f_{\alpha_1}(\theta_1^-) < y < \underline{y}^f_{\alpha_1}(\theta_1) = \overline{s}_{\alpha_1}(y)$. Suppose there is some other type (α_2, θ_2) for which $\underline{y}^f_{\alpha_2}(\theta_2) = \underline{y}^f_{\alpha_1}(\theta_1)$. Then (6) implies that $\frac{w^s_{\alpha_1}(\theta_1)}{w^f_{\alpha_1}(\theta_1)} = \frac{w^s_{\alpha_2}(\theta_2)}{w^f_{\alpha_2}(\theta_2)}$, and then (8) implies that a moonlighting worker of type (α_2, θ_2) is indifferent between $\underline{y}^f_{\alpha_1}(\theta_1^-)$ and $\underline{y}^f_{\alpha_1}(\theta_1)$. Thus, $\overline{s}_{\alpha_2}(y) = \overline{s}_{\alpha_1}(y)$.

Finally, the average extensive margin term can be expressed as in formula (59) by moving the summation sign under the integral and then multiplying and dividing the sum by $\overline{\Delta T}(z)$, defined in the statement of the theorem. □

The formula is remarkably similar to the one found in the case of one-dimensional heterogeneity in productivities. There are two differences. First, raising marginal tax rate at a single income level may lead to intensive margin responses of moonlighting workers at multiple formal income levels. Suppose the marginal tax rate at y is increased. There can be moonlighting workers of type α_1 at formal earnings y responding marginally, as well as moonlighting workers of type α_2 at formal earnings $y' > y$ responding by jumping down. If the tax schedule features multiple regions of regressivity, a change of marginal tax rate can trigger jump responses of moonlighting workers at multiple earnings levels. In contrast, in the single-dimensional case considered in the main text the moonlighting workers always responded at a single earnings level. The second difference concerns the extensive margin responses. Formal workers with identical earnings z but different types α can have different propensity to join the shadow economy (controlled by the semi-elasticity $\pi_\alpha(z)$) as well as different earnings conditional on joining the shadow economy (implying different $\Delta T_\alpha(z)$). Thus, we need to consider the average semi-elasticity of density of formal workers as well as the average tax revenue loss from joining the informal sector.

D. Estimation details

We use the 2013 wave of the household survey by the official statistical agency of Colombia (DANE). We restrict attention to individuals aged 24-50 years without children (34,000 observations). The indicator variable I^f is set equal to one if the worker reports to be affiliated to all three components of social security: pension system, health insurance and labor accidents insurance. I^f indicates formality of the main job and does not imply that the worker is exclusively formal.

We use two questions of the survey to construct our measure of the hourly wage $\mathcal{W}$. First, the worker is asked what was her income at the main job last month.

Table 2: Description of variables and parameter estimates

Variable	**Description**	**Estimate**	**Std. error**
Productivity schedules			
$\log(w_0^f)$	formal log productivity at the bottom	0.003	(1e-4)
γ^f	slope of formal log productivity	4.64	(.06)
$\log(w_0^s)$	informal log productivity at the bottom	0.006	(1e-4)
γ^s	slope of informal log productivity	2.90	(.06)
α_w	tail parameter of w^f distribution	2.25	(.03)
Type distribution			
σ_ϵ	std. deviation of θ given observables	0.09	(2e-3)
σ_κ	parameter of the fixed cost distribution	1.38	(0.03)
α_κ	parameter of the fixed cost distribution	0.88	(.01)
w_κ	parameter of the fixed cost distribution	0.018	(2e-4)
σ_u	std. dev. of the wage measurement error	0.53	(3e-3)
Preferences			
Γ	weight on labor supply in the utility function	0.032	(8e-4)
Coefficients of variables included in X			
Gender	Dummy variable equal to 1 for women	-0.08	(2e-3)
Age	Age of the worker	0.04	(1e-4)
Age^2	Age squared	-5e-4	(6e-6)
Educ	Number of education years	0.02	(5e-4)
Degree	Highest degree achieved (No degree to Doctorate)	0.05	(1e-3)
Work	Number of months worked in the last year	0.02	(7e-4)
Exper	Number of months worked in the last job	6e-5	(6e-5)
1stJob	Dummy for the first job (1 if it is the first job)	2e-4	(2e-5)
S-Man	Dummy for the manufacturing sector	-0.04	(1e-3)
S-Fin	Dummy for financial intermediation	0.14	(3e-3)
S-Ret	Dummy for the sales and retailers sector	-0.012	(3e-4)
B-city	Dummy for a firm in one of the two largest cities	0.10	(3e-3)
Size	Categories for the number of workers	0.11	(2e-3)
Lib	Dummy for a liberal occupation	0.25	(6e-3)
Admin	Dummy for an administrative task	-5e-3	(1e-4)
Seller	Dummy for sellers and related	4e-3	(1e-4)
Services	Dummy for a service task	-0.02	(6e-4)
Union	Dummy for labor union affiliation (1 if yes)	0.17	(4e-3)
Agency	Dummy for agency hiring (1 if yes)	-0.015	(3e-4)
Senior	Number of months of the worker in the firm	7e-4	(1e-5)

Note: Standard errors are obtained by Case Resampling Bootstrap using 150 draws.

Second, what is the number of hours she 'normally' works at that job. We use the ratio of the reported income and hours in those questions to compute our measure of the hourly wage. Since the 'normal' number of hours need not to correspond to last month's number of hours we explicitly introduce a measurement error.[42] If the worker is identified to be formal at the main job, we include the statutory payroll taxes that are paid by the employer in the computation of the pre-tax income at the main job. Finally, we construct the empirical tax and transfer schedule by taking into account the personal income tax, payroll taxes which are not linked to benefits, and cash transfers to low income individuals.

The parameter estimates are reported in Table 2. The estimated density of types and the model fit are shown in Figure 4 in the main text.

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[42] We further assume that survey respondents correctly reveal their gross income from the main job, regardless of whether the main job is formal or informal. Other papers making this assumption include Meghir et al. (2015) for Brazil and López García (2015) for Chile.

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