Working Time Reduction and Employment in a Finite World

Jean-François Fagnart[*], Marc Germain[†] and Bruno Van der Linden[‡]

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Abstract

We study the consequences of a working time reduction (WTR hereafter) in an exogenous growth model with unemployment (due to efficiency wage considerations) and a renewable natural resource. The resource is an essential input whose marginal productivity is bounded by physical laws. In the laissez-faire equilibrium, firms set headcount employment, working time and a wage level which affects workers' effort. We show that if a WTR always decreases the total number of worked hours, its impact on the number of (un)employed crucially depends on the relative scarcity of the resource. If the ressource inflow is unlimited, the economy converges toward a balanced growth path and a WTR lowers the levels of output, employment and wages along this path, without affecting their growth rate. When the resource inflow is finite, the economy converges toward a stationary state. In this case, a WTR increases the stationary level of hourly wages and employment if the resource is scarce enough (which is for instance the case if the labour and capital saving technical progress is unbounded). Furthermore, the long-term elasticity of employment (resp., of the hourly wage) to the cut in hours is larger (resp., smaller) when the resource is scarcer. The transitory dynamics toward the stationary state is studied numerically. As far as the impact of a WTR on employment and wage are concerned, this analysis confirms the results put forward for the stationary state.

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[*]CEREC, Université Saint-Louis - Bruxelles and IRES/LIDAM, UCLouvain. Corresponding author: 43, boulevard du Jardin Botanique, 1000 Bruxelles, Belgium, jean-francois.fagnart@usaintlouis.be

[†]LEM-CNRS (UMR 9221), Université de Lille and IRES/LIDAM, UCLouvain.

[‡]FNRS and IRES/LIDAM, UCLouvain; CESifo; IZA.

1 Introduction

For a long time, economists have been worried by unemployment, which is chronically or structurally present all over the globe. Its causes and the alternative policy interventions to curb unemployment have been analysed by many scholars. Among these policies, the reduction of working time (WTR hereafter) has sometimes been advocated and implemented, typically with mixed effects on (un)employment. In particular, the theoretical literature does not clearly support the view that a WTR would be an effective remedy against unemployment: a positive effect of WTR on employment is at best a short run result that does not hold once capital accumulation (or entry of firms) is taken into account (see the survey in section 2).

The mainstream literature on WTR has however neglected environmental constraints[1] and has analysed the effects of a WTR in frameworks where human productions do not consume any natural resource. Environmental constraints can no longer be ignored and we show that a stronger case can be made in favour of the effectiveness of WTR in an economy where a limited (though renewable) natural resource is an essential input.

Environmental limits to human activities may be of two types. As a provider of natural resources (in short, as a source), the environment could constrain the development of economic activity and employment in several ways[2]. As a receptacle of human pollutions (in short, as a sink), the environment has a limited absorption capacity: pollutions induce environmental damage that can ultimately impact economic activity in general and employment in particular. With regard to these two environmental limits, there remains however a kind of asymmetry in the mainstream literature depending on whether it considers the environment as a source or a sink. On the one hand, it is increasingly accepted that our ecosystems have a limited capacity as a receptacle for our polluting activities and that this can constrain economic activity and growth. On the other hand, economic growth seems to be freed from the limits of the same ecosystems as providers of resources[3]. The latter position finds its root in the optimistic assumptions made about 1) the substitution possibilities between human factors and natural resources and 2) the potential of resource saving technological progress. But once, in accordance with the laws of physics, it is recognised that both the substitution possibilities between human and natural inputs and the potential of this technical progress are limited, the finite nature of resources appears as another limit to growth, even though this issue may not seem as urgent as pollution[4].

In the present paper, we intentionally disregard pollution, or more generally, environmental damage. Our purpose is not to minimise this acute problem but to put forward that the impact of the environmental constraints on employment is not only linked to pollution[5]. In particular, the effect that a WTR can have on employment in an economy with finite holds true even if resource consumption is perfectly "clean". More precisely, we show that if a WTR reduces the total number of hours worked, its medium and long-run effects on (un)employment crucially depend on the relative scarcity of the resource: if the negative results of the theoretical literature remain true

[1] Let us however mention that several ecological economists (see a.o. Victor and Rosenbluth [2007], Jackson and Victor [2011], Victor [2012]) have analysed work-sharing policies as a way of avoiding a surge in unemployment in a context of low growth or degrowth. But to the best of our understanding, their approach relies on an accounting exercise in which the total number of hours worked does no react endogenously to a change in working time.

[2] At a very aggregate level like that adopted here, the problem of natural resources is not a resource shortage, but rather a decline in their quality and/or a more difficult exploitation of marginal resources, both forcing the economy to devote more and more human factors (labour and capital) to the exploitation of resources rather than to final production, with deleterious consequences for investment, capital accumulation and growth.

[3] As noted by Hassler et al. [2016] in the Handbook of Macroeconomics, the concern about the finiteness of natural resources which was present in the literature of the nineteen seventies "did not have a long lasting-impact on macroeconomics" (p. 1900).

[4] Let us however note that environmental damage does not only result from the emission of pollutants but also from the very exploitation of some natural resources and the destruction of the ecosystems which host them. This aspect of environmental damage is nothing but a manifestation of the finite nature of resources.

[5] A symmetric approach to ours can be found in the static general equilibrium models of Aubert and Chiroleu-Assouline, (2019) or Heutel and Zhang, (2020): in frameworks with pollution but without resource, they study the incidence of environmental policies (green tax) when the labour market is imperfectly competitive.

when the resource is, in relative terms, sufficiently abundant, a WTR turns out to be sustainably conducive to more employment when the resource is scarce enough.

We develop, calibrate and simulate a one-sector deterministic Ramsey exogenous growth model with unemployment and a renewable natural resource whose productivity is bounded from above in accordance with the physical laws. The resource is free but the quantity of capital and labour needed to capture and transform it increases with its exploitation rate. An exogenous technical progress reduces the quantity of natural resource needed to produce the good, yet with a strictly positive lower-bound: the process of dematerialisation of production is limited. Another exogenous technical progress increases the productivity of capital and labour, potentially without limit. Firms set their production plan, wages, hours worked, headcount employment and capital use, while workers choose their work effort, consume and save. Unemployment is endogenous in the tradition of the efficiency wage literature, and more specifically the gift-exchange version of it (Akerlof, 1982). The choice of this tradition is doubly motivated. On the one hand, several contributions to the efficiency wage literature (see the survey in the next section) have analysed the effects of WTR in the absence of any resource constraint and provide an interesting point of comparison. On the other hand, as we model a world economy, we avoid introducing unions and labour market institutions (such as employment protection legislation, minimum wages,...) that are present in some rich countries but are not generalised worldwide.

The long-run properties of this economy are successively studied without and with resource limits. In the former case, the long-run equilibrium is a balanced growth but in the latter, it is a steady state with a finite level of aggregate output. Along the balanced growth path of an unconstrained economy, a WTR would be counter-productive. But in an economy with finite natural resources and unlimited capital and labour saving technical progress, it reduces the long-run unemployment rate and is welfare enhancing. When human factor technical progress is instead bounded, these steady-state properties are qualitatively preserved when the natural resource is scarce enough or, equivalently, when its exploitation rate is high enough.

We analyse the transitory dynamics of our economy and the impact of a WTR numerically. In a benchmark case calibrated on world data and with unlimited capital and labour saving technical progress, a WTR has a positive effect on employment during the whole transitory dynamics and this effect is stronger in periods where the employment rate is lower. A sensitivity analysis confirms, for the transitory dynamics, that a WTR increases employment more and the hourly wage less when the resource constraint is more stringent.

The rest of the paper is organised as follows. Section 2 summarizes the literature about the effects of a WTR. Section 3 presents the theoretical framework, and Section 4 its solution. The latter section also presents the properties of a WTR in a steady state. Section 5 develops the numerical analysis of the dynamic adjustment of the modeled economy. Section 6 concludes.

2 Literature Review on Working Time Reduction

Since the eighties, the impacts of the regulation of working time has been studied in a range of theoretical set-ups without natural resource and most often without productive capital (or without capital adjustments). In the efficiency wage literature, firms choose labour demand and the wage level subject to a relationship describing in-work effort or quit behaviour as a function of some model-specific determinants. In chapter 10 of their book on unemployment, Layard et al. [1991] develop a streamlined model with homogeneous workers and firms where these determinants are the unemployment rate[6] and an indicator of the generosity of the pay policy of the firm. Layard et al. [1991] assume that this generosity is measured by the ratio between the real wage paid by the firm and the average wage in the economy (supposed to be the reference level for the workers). In a symmetric equilibrium, this ratio is equal to one, which implies that the in-work effort level

[6]This indicator captures workers' prospect outside the firm. In a way or another, a higher risk of being unemployed provides an incentive to put effort on the job.

is then independent of the wage level. This property makes, by construction, the equilibrium unemployment rate independent of working time, so that exogenous manipulation of working time cannot affect unemployment (see Layard et al., 1991, p. 503). The key assumption that underlies this result can however be questioned. For instance, Danthine and Kurmann [2004] argue that "the positive incentive effect of a larger own wage is stronger than the negative effect of a higher comparison wage" (p. 112). And yet one can check that in a model à la Layard et al. [1991] with an effort function implying a positive effect of the wage level on the in-work effort *in equilibrium,* work-sharing can reduce unemployment. Before Layard et al. [1991], Hoel and Vale [1986] studied the effects of a WTR in an efficiency wage model with quit behaviour and training costs. The assumptions they make on the quit rate function are *mutatis mutandis* equivalent to those made by Layard et al. [1991] on their effort function: the quit rate depends negatively on both the unemployment rate and the ratio between the wage paid by the firm and the average wage in the economy. Consequently, the quit behaviour of workers in a symmetric equilibrium depends on the unemployment rate but not on the wage level. Because work-sharing increases training costs, the authors then conclude that a WTR affects (un)employment unfavourably. In the final discussion of their paper, they however consider an alternative specification for the quit behaviour, which leads them to conclude their analysis in a rather nuanced and cautious way.

In a model without capital, Rocheteau [2002] mixes a search and matching framework and a moral hazard problem (workers having the possibility to shirk on the job[7]). He shows that the impact of a WTR depends on whether efficiency wage considerations matter or not: a WTR has a positive effect on equilibrium employment when the no-shirking-constraint is binding, i.e. when unemployment is high enough; but it always worsens the labour market situation when the no-shirking condition does not bind, i.e. when unemployment is low enough.

The literature on collective bargaining has also analysed the consequences of work-sharing. In the partial equilibrium settings (see e.g. Calmfors, 1985, Booth and Schiantarelli, 1987, and Booth and Ravaillon,1993), a WTR affects employment negatively or at best ambiguously. In a highly stylised model of a unionised economy, Layard et al. [1991] conclude in the same way as in their efficiency wage model: a WTR does not affect the equilibrium unemployment rate (see p. 503-4). In a much more general and dynamic framework with endogenous labour market participation and an endogenous number of firms, Cahuc and Granier [1997] obtain a possible positive effect of work-sharing on employment at given number of firms but reach the same overall conclusion as Layard et al. [1991] once the number of firms has adjusted. In a search and matching model with bargaining over wage and hours, Marimon and Zilibotti [2000] conclude that a sufficiently small reduction in working hours below its *laissez-faire* value may have a favourable effect on equilibrium employment at given capital stock. But it is no longer the case once capital becomes endogenous. Hence, for the authors, "the positive employment and welfare effects which may materialise in the short run are likely to vanish as firms adjust their productive capacity." (p. 1310.)

To sum up, the theoretical literature provides mixed conclusions about the effect of a WTR on (un)employment. Moreover, when it prevails, the result of a positive employment effect of work-sharing typically appears as a short-term one: it is obtained in frameworks in which productive capital is neglected or taken as given but it is not confirmed once productive capital (or the number of firms) becomes endogenous as in the last two quoted papers. We show that the presence of an essential natural resource may lead to a different conclusion. More precisely, we will confirm the above conclusion when the resource is, in relative terms, sufficiently abundant. But when the resource is scarce enough, a WTR have both short and long run positive effects on employment.

Several reforms have historically cut working hours in order to hopefully curb a rise in or a high level of unemployment. All in all, the empirical evaluation literature[8] indicates that reductions of the standard working time are often, by law or not, accompanied by increases in hourly wages and their net impact on employment is typically gloomy except in specific contexts (strong recessions)

[7]See Shapiro and Stiglitz [1984].

[8]See Hunt [1999], Crépon and Kramarz [2002],Andrews et al. [2005], Skuterud [2007], Crépon and Kramarz [2008], Chemin and Wasmer [2009], Raposo and van Ours [2010a], Raposo and van Ours [2010b], Taylor [2011], Askenazy [2013], Sánchez [2013], and Kawaguchi et al. [2017]

or when they are accompanied by other reforms. This empirical literature is obviously exploiting data of periods where the environmental constraints were less acute than currently and in the future. Hence, in the context of the present study, its conclusions are at best weakly informative.

3 The Economy

This section develops a streamlined deterministic growth model of a world economy[9] with a finite renewable natural resource and populated by infinitely-lived agents. There are three markets: perfectly competitive good and capital markets and an imperfectly competitive labour market. The final good is produced by identical private firms which use labour and capital ("agent inputs" in the taxonomy of Anderson, 1987) as well as a material input. The latter is obtained by exploiting a renewable natural resource (henceforth "the resource" for short). It is assumed to be in free access but its exploitation requires agents inputs and is therefore costly. Furthermore, as in a.o. Dasgupta and Heal (1979), exploiting the ressource becomes more intensive in agent inputs when the aggregate available resource stock is lower or, equivalently, when its exploitation rate is higher. The relative resource scarcity so affects production costs and, thereby, economic activity.

The production process is improved through time by two forms of exogenous technological progress, one that increases the productivity of capital and labour, the other one that dematerialises final production, i.e. that reduces the quantity of natural resource needed to produce the final good. This dematerialising technical progress is however bounded by the physical laws that govern any transformation of matter, including human productions. These laws preclude any technological assumption that would make possible an infinite marginal productivity of the resource.[10] Consequently, if the stock of renewable resource is finite, the economy tends toward a stationary state with a finite income level per capita (see Section 4).

In order to keep the model as simple as possible, we model the production technology in a way that does not require to describe the allocation of capital and labour to resource exploitation on the one hand and to final production on the other hand. To this end, we assume that the production process is described by two relationships which respectively give 1) the resource requirement of final output and 2) the combination of agent inputs necessary to the resource transformation. This amounts to assuming that capital and labour are substitutable but that there is no direct substitution possibilities between agent and resource inputs.[11] This assumption is only made for simplicity but it is not at all essential to our results about the impact of a working time reduction policy as we explain in section 4.3.4.

Labour is homogeneous but working time, work effort and headcount are distinguished. We let firms decide over hours worked, labour demand and wages. In the tradition of the efficiency wage literature, and more specifically the so-called gift-exchange version of it (Akerlof, 1982), the employees of a firm choose their (non-contractible) work effort. The latter is affected by the firm's wage policy and by working conditions in the rest of the economy. This labour market imperfection leads to a positive equilibrium unemployment rate. It is indirectly affected by the resource scarcity through its impact on economic activity and labour demand.

[9]The closed economy hypothesis is traditional in growth theory. Its interest here is also to "force" the economy to fully support its environmental constraint (here resource constraint), without the possibility of bypassing it through trade with the rest of the world.

[10]See a.o. Anderson [1987] and Krysiak [1985]. In the present framework with a material input, the physical law taken into account is the law of mass conservation (or material balance principle). Baumgärtner [2004] shows in particular that production functions that verify the Inada conditions are inconsistent with this law. Complementarily, in a framework with energy, Meran [2019] shows that thermodynamic constraints imply that the productivity of energy and the energy saving technical progress are necessarly bounded.

[11]Anderson [1987] shows that for a given technology, substitution possibilities between material and agent inputs are indirect and only exist if the use of more agent inputs leads to a lesser waste of resource in its transformation process. As there is no waste of resource in the present model, this indirect possibility of substitution is absent here.

3.1 Families of Consumers-Workers

In the model economy, some individuals work and earn a wage income while others are unemployed. Since income inequality is not the focus of our paper, we model the worker-consumer side of the economy in a way that eliminates the consequences of income inequality. To this end, we consider that the economy is populated by M families, each consisting of n_t individuals in period t. In t, the population size (understood as the labour force) is thus $P_t = M\,n_t$. Each family member has an infinite horizon and may be employed or not in a given period t. When employed, she supplies h_t work hours with a variable effort level e_t; she is paid at an hourly real wage w_t, with h_t and w_t chosen by firms (see later). When unemployed, she earns no labour income or unemployment allowance. We assume that unemployment is equally spread across families[12] so that the proportion of unemployed in a family is equal to the aggregate unemployment rate $u_t = 1 - L_t/P_t$.

Decisions are taken at the family level. A family consumes and saves by accumulating productive capital. The depreciation rate of productive capital is unitary, which reflects that the length of a time period is long enough[13]. The capital stock $\tilde{k}_t$ accumulated by a family at the end of period $t-1$ is rent to firms during period t at a real rental price v_t.

In each period, the number of workers by family is given by $L_t/M \leq n_t$ where L_t is the aggregate employment level resulting from firms' choices, with $L_t \leq P_t$. If the final good is chosen as *numéraire*, the budget constraint of a family in period t is thus given by

$$c_t + \widetilde{k}_{t+1} = v_t \widetilde{k}_t + w_t h_t \frac{L_t}{M}, \qquad \forall t = 1, ..., T \tag{1}$$

where c_t is the consumption level of the family in t and $\tilde{k}_{t+1}$ is the capital stock accumulated at the end of period t, k_1 being given; the right-hand side of (1) represents the total income of the family in t, consisting both of capital income, $v_t\widetilde{k}_t$, and of labour income $w_t h_t L_t/M$.

A family chooses c_t, $\tilde{k}_{t+1}$ and the work effort of its employed members, e_t, so as maximise the discounted sum of the instantaneous (separable) utility of its average member:

$$\max_{\{c_t, \tilde{k}_{t+1}, e_t\}_{t\geq 1}} \sum_{t=1}^{\infty} \beta^t \left[\ln\left(\frac{c_t}{n_t}\right) - \left[d(h_t) + \left[e_t - g\left(w_t, \overline{w}_t, u_t\right)\right]^2 \right] \frac{L_t}{P_t} \right], \tag{2}$$

subject to (1) with k_1 given. β (with $0 < \beta < 1$) is the discount factor. The multiplicative term in front of L_t/P_t measures the disutility of work hours and effort for an employed member of the family. Function $d(h_t)$, the disutility of work hours, is increasing and convex: $d'(.) > 0, d''(.) \geq 0$. Along the idea of Akerlof [1982], the non-contractible work effort is chosen by workers according to a social norm of fairness. Various social experiments provide support for this mechanism[14]. Collard and de la Croix [2000], Danthine and Kurmann [2004] and de la Croix et al. [2009] among others integrated this mechanism in the analysis of business cycles. We follow their specification by assuming in (2) that the utility level reached in each period is affected by a quadratic loss function of the discrepancy between the actual work effort and the effort level that is considered as fair, namely the function $g(.)$. As in de la Croix et al. [2009], it is increasing in the wage paid to the worker and the unemployment rate but decreasing in the average wage $\bar{w}_t$ in the economy.[15]

[12] This assumption and the one that decisions are taken at the level of the family neutralise the problem of income inequality between workers and unemployed (see also Danthine and Kurmann, 2004). Collard and de la Croix [2000] propose an alternative formulation that is perfectly equivalent to ours at the aggregate level.

[13] The same assumption is made e.g. by Hassler et al. [2016], p. 1908.

[14] Laboratory experiments generally find that on average workers exert additional effort when their employer offers them a higher wage rate (see e.g. Fehr et al., 1993, and Brandts and Charness, 2004). Field experiments lead to more mixed conclusions. For instance, Gneezy and List [2006] conclude that this effect is present but only temporary. However, Cohn et al. [2015] find strong and lasting support for the gift-exchange hypothesis.

[15] In the above-mentioned references, the function g also depends of past wages. Given the length of a period in the present paper, the presence of this lagged wage seems to us less needed. Introducing past wages would in addition lead to a much less tractable framework. See the discussion in Danthine and Kurmann [2004] and [2010].

The optimality conditions of problem (2) straightforwardly lead to

$$\frac{c_{t+1}}{c_t} = \beta v_{t+1} \tag{3}$$

$$e_t = g(w_t, \overline{w}_t, u_t). \tag{4}$$

Condition (3) describes the standard consumption smoothing behaviour, the rental price of capital v_{t+1} being equivalent (when the depreciation rate is unitary) to 1 plus the real interest rate. Combining (3) and (1) gives the evolution of the capital stock, which must also verify the transversality condition. The optimal effort level is given by (4) gives and has the properties of function $g(\cdot)$.

3.2 Final good sector

The final good sector consists of N perfectly competitive and identical firms. Production activities require capital, labour and the natural resource. The production process is described by two relationships which respectively give 1) the resource requirement of final output and 2) the combination of capital and labour necessary to the resource transformation.

1) In order to produce y_t units of final good, a firm needs x_t resource units, with x_t given by

$$x_t = \mu_t y_t \tag{5}$$

where $\mu_t > 0$ is the resource content of one unit of output and is a technological factor exogenous at the firm level.

2) In order to produce y_t, or equivalently to capture and transform x_t resource units, capital k_t and labour are required. The labour input is characterised by three dimensions: the number of employed workers, l_t, their effort at work e_t and the length of the working time h_t, which also impacts capital utilisation. In order to transform x_t resource units, agent inputs (k_t, l_t, h_t, e_t) must be combined according to a technology $\mathcal{F}$ and in such a way that

$$\frac{\eta_t}{B(E_t)}\mathcal{F}(k_t, l_t, h_t, e_t) = x_t \tag{6}$$

where $\eta_t > 0$ is a productivity factor of agent inputs and function $\mathcal{F}(k_t, l_t, h_t, e_t)$ is strictly increasing and concave in its arguments. Function $B(E_t)$ describes the congestion externality affecting resource exploitation and is strictly increasing in the (aggregate) resource exploitation rate E_t:

$$E_t =_{\text{def}} X_t/R_t \quad \text{with} \quad 0 \le E_t \le 1. \tag{7}$$

Variable X_t is the aggregate resource consumption in t and R_t is the total resource stock at the beginning of period t. Function $B(E_t)$ verifies $B(0) = 1$, $B'(E) > 0$, $B''(E) > 0$ and $B(1) \to +\infty$. This means that the resource exploitation becomes increasingly intensive in agent inputs when E_t rises. These assumptions formalise the generally accepted view that the exploitation of natural resources is characterised by increasing marginal costs.[16]

Appendix A.1 rationalises the following functional form for $\mathcal{F}$:

$$\mathcal{F}(k_t, l_t, h_t, e_t) = U(h_t)k_t^{\alpha}\left[e_t l_t\right]^{1-\alpha} \tag{8}$$

where $0 < \alpha < 1$. Function $U(h)$ is such that $U(0) = 0$, $U'(h_t) > 0$, $\lim_{h\to\infty} U'(h) = 0$ and the elasticity of $U(h)$ with respect to h is decreasing in h and larger than $1 - \alpha$ at $h = 0$ (see later).[17] As Appendix A.1 shows, function $U(\cdot)$ does not simply reflects the positive effect of h

[16]See e.g. Fagnart and Germain [2011] who rationalise this assumption in a growth model with renewable resource.

[17]This assumption of a decreasing elasticity is compatible with various functional forms for U (implying either an always concave function U or a function U first convex, next concave for sufficiently large values of h). It however excludes an isoelastic function U but this exclusion is only necessary in the case of a Cobb-Douglas relationship between capital and labour as it will become clear in the sequel.

on the quantity of labour input at given e_t and l_t: it also incorporates the positive impact of the working time on the use of capital.

As E_t is a macroeconomic variable that each firm perceives as independent of its own decisions, (6) (with (8)) implies that returns-to-scale are constant at the micro level. The optimal size of a final firm is thus indeterminate and the decision problem of the firm must be written as a cost-minimisation problem: for a given output level, each firm chooses (i) its capital and resource requirements, (ii) its employment level, (iii) the length of the working time and (iv) the hourly wage it offers so as to induce the appropriate work effort. Given (5), the choice of x_t is tight to the output level y_t ($x_t = \mu_t y_t$) and optimisation bears on the choice of k_t, l_t, h_t and w_t. Given (5) and (6), the technological constraint to produce a given output level y_t is given by

$$\frac{\eta_t}{\mu_t B(E_t)} U(h_t) k_t^{\alpha} \left[e_t l_t\right]^{1-\alpha} = y_t. \tag{9}$$

Relationships (5) and (9) are *in fine* equivalent to a Leontief technology between the resource input and the human factors in the production of final goods. A parallel can be drawn here between the technological relationship (9) and that in Hassler et al. [2016] (e.g. p. 1938-9). In both cases but via a different mechanism[18], a stronger pressure of human activities on the Earth's capacity, either as a source (in our case) or as a sink (in Hassler *et al*), has a negative impact on the productivity of human factors in final productions.

In each period t, the representative firm thus chooses k_t, l_t, w_t, h_t so as to solve

$$\min_{\{k_t, l_t, w_t, h_t\}} \; v_t k_t + w_t h_t l_t \tag{10}$$

under constraint (9) and (4). This problem is solved in Appendix A.2, which shows that the optimality conditions with respect to k_t, l_t, w_t and h_t may be written respectively as:

$$v_t k_t = \alpha \, y_t \tag{11}$$

$$w_t h_t l_t = [1-\alpha] \, y_t \tag{12}$$

$$\frac{w_t}{e_t} \frac{\partial g\left(w_t, \bar{w}_t, u_t\right)}{\partial w_t} = 1 \tag{13}$$

$$h_t \frac{U'(h_t)}{U(h_t)} = 1-\alpha. \tag{14}$$

Conditions (11) and (12) are standard in the case of a Cobb-Douglas relationship between capital and labour: k_t and l_t are chosen in a way such that capital and labour shares stay constant. Condition (13) gives the optimal wage policy and is a modified Solow condition (Solow, 1981). Given the assumptions on $U(h_t)$, a solution to condition (14) exists and is unique. This condition implies that firms choose a constant working time: $h_t = \bar{h}$. This results follows from the Cobb Douglas assumption in (9) and can be understood by considering the marginal choice made by a firm between the number of work hours and the number of workers. Increasing hours (resp. employment) by 1% raises the wage bill by 1% and output by a percentage equal to the elasticity of $F(k_t, l_t, h_t, e_t)$ with respect to hours (resp. employment). At the lowest cost, hours and employment must thus be chosen in a way such that the elasticity of F with respect to hours is equal to the elasticity of F with respect to employment. Since the latter elasticity is a constant $(1-\alpha)$ in the case of a Cobb-Douglas, the former is equal to the same constant at the solution of problem (10).

3.3 Macroeconomic Equilibrium

At the aggregate level, final output, resource consumption, employment and productive capital are respectively given by $Y_t = N y_t$, $X_t = N x_t = N \mu_t y_t = \mu_t Y_t$, $L_t = N l_t$ and $K_t = N k_t$. Given (5),

[18] Here, this mechanism is an increasing exploitation cost of the resource (a more intensive resource use makes its exploitation more intensive in labour and capital); in Hassler *et al*, it is a pollution externality that causes damage and thereby decreases the total factor productivity.

the aggregation of the technological relationship (6) leads to the following macro relationship

$$\eta_t U(h_t) K_t^{\alpha} \left[e_t L_t\right]^{1-\alpha} = B(E_t) X_t \tag{15}$$

At the macroeconomic level, (11) and (12) become:

$$v_t K_t = \alpha Y_t \tag{16}$$

$$w_t h_t L_t = [1-\alpha] Y_t \tag{17}$$

The capital market clearing requires that $K_t = N k_t = M \widetilde{k}_t$. On the final good market,

$$Y_t = C_t + K_{t+1} \tag{18}$$

where $C_t = M c_t$ is aggregate private consumption and K_{t+1} is investment (recall the assumptions of a unitary depreciation rate and of a period time to build). Furthermore C_t must verify (3):

$$\frac{C_{t+1}}{C_t} = \beta v_{t+1}. \tag{19}$$

As in de la Croix et al. [2009], we assume that the effort function $g(.)$ is given by

$$g\left(w_t, \overline{w}_t, 1 - \frac{L_t}{P_t}\right) = \frac{1}{\psi}\left[\phi_1 w_t^{\psi} - \phi_2 \overline{w}_t^{\psi} - \phi_3 \left[1 - \frac{L_t}{P_t}\right]^{-\psi\phi_4}\right] \tag{20}$$

with $\phi_1, \phi_2, \phi_3, \phi_4 > 0$, $\phi_1 > \phi_2$ and $0 < \psi < 1 - \phi_2/\phi_1$ (for reasons explained later). We furthermore assume that $\phi_1 - \phi_2 - \phi_3 = 0$.[19] Consequently, the wage elasticity of the effort function is equal to

$$\frac{w_t}{e_t}\frac{\partial e_t}{\partial w_t} = \phi_1 \frac{{w_t}^{\psi}}{e_t}.$$

Given (13), this implies an effort level increasing in the wage level:

$$e_t = \phi_1 w_t^{\psi}. \tag{21}$$

At macroeconomic equilibrium, individual and average wage coincide ($w_t = \overline{w}_t, \forall t$): (20) becomes

$$e_t = \frac{\phi_1 - \phi_2}{\psi} w_t^{\psi} - \frac{\phi_3}{\psi}\left[1 - \frac{L_t}{P}\right]^{-\psi\phi_4}. \tag{22}$$

3.4 Natural resource dynamics

At the beginning of any period t, the economy is endowed with a stock of the natural resource R_t. The latter is depleted both by natural depreciation and by the exploitation by man; it is replenished by an exogenous inflow $F_t \geq 0$. Given that X_t resource units are consumed by final production in period t, the resource stock evolves as follows:

$$R_{t+1} - R_t = F_t - \delta_R R_t - X_t, \tag{23}$$

where $\delta_R \geq 0$ is the exogenous natural depreciation rate of the resource.

[19] Under this assumption, the right-hand side of (20) is linear in the logarithms of its arguments when $\psi \to 0$: $e_t = \phi_1 \ln w_t - \phi_2 \ln \bar{w}_t + \phi_3' \ln u_t$, with $\phi_3' = \phi_3\phi_4$, which corresponds to the function considered by Danthine and Kurmann [2004] and leads to a constant effort level.

3.5 Technical progress

There are two (exogenous) sources of technical progress. A resource saving progress reduces the resource content of one unit of input: formally said, $\mu_{t+1} \leq \mu_t, \forall t$. As explained in the introductory paragraphs of section 3, this dematerialising technical progress is however bounded by physical laws: the resource content of one unit of output is bounded from below, i.e.

$$\lim_{t \to +\infty} \mu_t = \underline{\mu} > 0. \tag{24}$$

The second form of technological progress raises the productivity of agent factors (capital and labour). Formally said, $\eta_t < \eta_{t+1}, \forall t$. If nothing guarantees that such productivity gains could go on without limit, their boundedness is not explicitly rooted in physical laws and is thus not systematically assumed in our analysis.

4 Model solution

4.1 Dynamic system

Equations (16), (18) and (19) lead to a remarkable property of the saving rate. Note first that (16) and (19) imply that $C_{t+1}/C_t = \beta v_{t+1} = \alpha\beta\, Y_{t+1}/K_{t+1}$. Equivalently $K_{t+1}/C_t = \alpha\beta\, Y_{t+1}/C_{t+1}$. Given (18), the last equality may be rewritten as

$$\frac{Y_t - C_t}{C_t} = \alpha\beta \frac{Y_{t+1}}{C_{t+1}}.$$

Let us introduce parameter s and variable θ_t defined as $s =_{\text{def}} \alpha\beta$ and $\theta_t =_{\text{def}} Y_t/C_t, \forall t$. θ_t is the inverse of the average propensity to consume. The above equation may then be rewritten as a first-order difference equation with constant coefficients:

$$\theta_t - 1 = s\, \theta_{t+1}. \tag{25}$$

Solving (25) forward over an infinite horizon leads to the following solution for θ_t in any $t \geq 1$:

$$\theta_t = \frac{1}{1-s} \quad \text{with} \quad s = \alpha\beta. \tag{26}$$

In this case, $C_t = [1-s]\, Y_t$: the families' propensity to save s is constant[20]. The higher the discount factor β and the elasticity of output with respect to capital α, the higher s.

Given (49) and (26), the macroeconomic model is described by the following dynamic system:

$$\eta_t U(\bar{h}) K_t^{\alpha} \left[e_t L_t\right]^{1-\alpha} = \mu_t Y_t B(E_t) \tag{27}$$

$$E_t = \frac{\mu_t Y_t}{R_t} \tag{28}$$

$$K_{t+1} = \alpha\beta Y_t \tag{29}$$

$$R_{t+1} - R_t = F_t - \delta_R R_t - \mu_t Y_t \tag{30}$$

$$w_t \bar{h} L_t = [1-\alpha] Y_t \tag{31}$$

$$e_t = \frac{\phi_1 - \phi_2}{\psi}\, w_t^{\psi} - \frac{\phi_3}{\psi}\left[1 - \frac{L_t}{P_t}\right]^{-\psi\phi_4} \tag{32}$$

$$e_t = \phi_1 w_t^{\psi}. \tag{33}$$

[20] As outlined by Fagnart and Germain [2011], this result follows from the combination of three assumptions (logarithmic instantaneous utility of consumption, unitary depreciation rate and Cobb Douglas relationship between capital and labour) and it only holds if agents face an in infinite horizon. See also Hassler et al. [2016].

It consists of 7 equations and 7 unknowns $K_t, Y_t, E_t, L_t, R_t, w_t, e_t$ $(t \geq 1)$, with initial conditions R_1 and K_1. Variables η_t, μ_t, F_t and P_t are exogenous. The model parameters are $\alpha, \beta, \delta_R, \phi_1, \phi_2, \phi_3, \psi$. The system (27)-(33) can be iteratively solved forward. With its solution, one may also compute C_t via (18), X_t via $X_t = \mu_t Y_t$ and v_t via (16).

Wage-setting relationship

Combining (32) and (33) gives an increasing relationship between hourly wage and employment:

$$w_t = w(L_t) =_{\text{def}} \left[\frac{\phi_3}{[1-\psi]\phi_1 - \phi_2}\right]^{1/\psi} \left[1 - \frac{L_t}{P_t}\right]^{-\phi_4}. \tag{34}$$

Since $\phi_3 > 0$ and w_t must be positive, we have to impose the following parametric restriction: $\phi_1 - \psi\phi_1 - \phi_2 > 0$, or equivalently $\psi < 1 - \phi_2/\phi_1$ as assumed earlier. Function $w(L_t)$ is increasing in L_t with $w(0) > 0$. It admits a vertical asymptote in case of full employment: $L_t = P_t$.

4.2 Long-run properties of an economy without resource limits

Under assumption (24) of a bounded resource-saving technical progress, this section and the next one analyse the long run properties of the economy, respectively in the absence and in the presence of an upper limit on the resource stock. The impact of a working time reduction policy (a.o. on wages and employment) turns out to be very different in the two cases.

4.2.1 Balanced growth path

If a) the resource inflow F_t and stock R_t are infinite and b) η_t grows unboundedly at constant rate $g_\eta > 0$, the economy admits a balanced growth path along which output grows at a constant rate.

When R_t is infinite, equation (30) disappears and (28) implies that $E_t = 0, \forall t$. Furthermore, even though $\lim_{t\to+\infty} Y_t = +\infty$, $\lim_{t\to+\infty} E_t = \lim_{t\to+\infty} \frac{\mu_t Y_t}{+\infty} = \lim_{t\to+\infty} 0 = 0$. Therefore, $\forall t \geq 1$,

$$B(E_t) = B(0) = 1. \tag{35}$$

Otherwise said, the resource never constrains the economy and, in particular, does not affect the features/properties of its balanced growth path. It is easily shown and unsurprising that the growth rate of output is then proportional to the growth rate of technical progress $g_\eta > 0$ and does not depend on any endogenous variable, and thus not on $\bar{h}$.

4.2.2 Impact of a Working Time Reduction Policy on the BGP

Hereafter we call a working time reduction policy (in short WTR) an exogenous and finite cut $\Delta h < 0$ evaluated at the level $\bar{h}$ firms would have freely chosen. We do not represent the agent that would take such a decision and limit the analysis to its implications.

If $\bar{h}$ does not impact the economy growth rate along the BGP, its value however influences the levels of output, employment and hourly wage along this path:

Proposition 1 *In a world without resource limits, a WTR lowers the levels of output, employment and wage along a balanced growth path.*

Proof. See Appendix A.3. ■

4.3 Long-run properties of an economy with finite resource

4.3.1 Stationary state with unbounded labour and capital saving technical progress

If a) the ressource inflow F_t and stock R_t are finite and b) η_t grows unboundedly at constant rate $g_\eta > 0$, final output cannot grow without limit and, in the long run, the economy reaches a stationary state with E tending toward 1. Intuitively said, when the productivity of agents inputs grows endlessly, firms are led and able to fully use the available resource; they then produce a finite level of output since the average productivity of the resource is bounded[21].

We use uppercase letters without time subscript to indicate the stationary state value of the corresponding variable. Given $E = 1$ and (28), the stationary level of output is such that

$$Y = \frac{R}{\underline{\mu}}. \tag{36}$$

Substituting (36) in (30) determines the stationary state value of the resource stock

$$R = \frac{F}{1 + \delta_R}, \tag{37}$$

which, given (36), implies a stationary output level equal to

$$Y = \frac{F/\underline{\mu}}{1 + \delta_R}. \tag{38}$$

When the resource is fully used (E tends to 1), long-run output is proportional to the relative abundance of the resource, which depends positively on the resource inflow F and negatively on the resource content of one unit of output $\underline{\mu}$. Unsurprisingly, when the productivity of agent inputs can grow without limit unlike that of material input, the quantities of labour and capital do not constrain what the economy is able to produce in the long run. In particular, long run output is not affected by the length of the working time. This would not be the case if the potential of technological progress on agent inputs was bounded, as Subsection 4.3.3 will show.

Expressions (38) and (31) jointly imply a stationary state relationship between the hourly wage, total hours worked and the relative resource abundance $F/\underline{\mu}$:

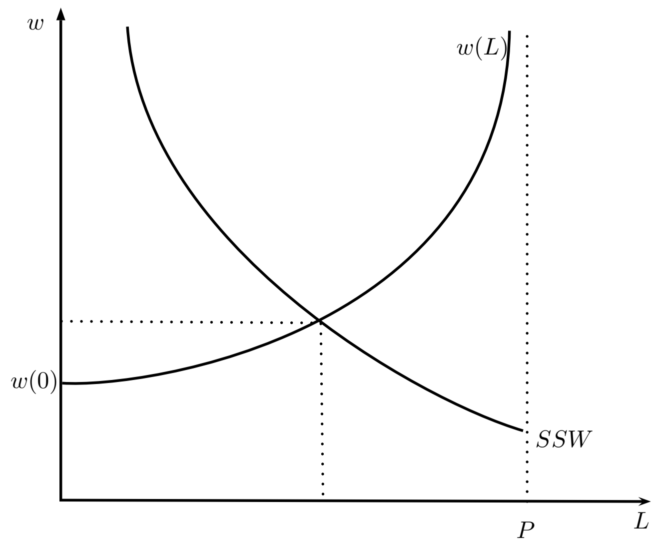
$$SSW \equiv w = \frac{1 - \alpha}{1 + \delta_R} \frac{F/\underline{\mu}}{\bar{h}L}. \tag{39}$$

SSW is a pseudo aggregate labour demand, which negatively links the hourly wage and employment L at given $\bar{h}$ and $F/\underline{\mu}$. Graphically, in the positive orthant of (L, w), it is a branch of hyperbola with a vertical asymptote at $L = 0$. This downward sloping labour demand (39) and the upward-sloping wage-setting relationship (34) both determine the stationary state equilibrium of the labour market as in Figure 1. Given the properties of the two curves, this equilibrium is necessarily unique and depends, via (39), on $F/\underline{\mu}$ as the following proposition establishes.

Proposition 2 *In a world with finite resource and unlimited labour and capital saving technical progress, a more stringent resource constraint, i.e. a lower value of $F/\underline{\mu}$, generates lower steady-state levels of output Y, employment L and earnings per worker wh.*

[21]Formally speaking, with finite levels of F and R, (30) implies a finite aggregate output level. Then, (29) implies a constant capital stock. Similarly, (31) and (34) jointly determine constant levels of employment and hourly wage. Via ((33)), effort is then constant as well. Consequently, given (27), E_t necessarily tends towards 1 if η_t keeps on growing at a constant rate $g_\eta > 0$. Indeed, on the left-hand side of (27), η_t tends towards infinity while all the endogenous variables reach stationary values. Hence, equality (27) can only be verified if its right-hand side tends towards infinity as well, which, with a finite Y_t, can only be the case if $E_t \to 1$.

Figure 1: Stationary state equilibrium of the labour market



Proof. Looking at (39), a lower value of $F/\underline{\mu}$ (either because F is less abundant or because the minimal resource content of a unit of output is higher), has a negative impact on the hourly wage firms can offer at given L. In Figure 1, a stricter resource constraint implies a downward shift of SSW and therefore lower levels of employment, hourly wage w and earnings (since h remains unchanged). Given (31), lower values of L and w also mean a lower output level. ■

4.3.2 A WTR increases aggregate employment but lowers earnings per worker

The following proposition establishes how a WTR affects employment, hourly wage, earnings and welfare in a stationary state. It also links the size of the changes in wage and employment to the intensity of the resource constraint.

Proposition 3 *In a world with finite resource and unlimited labour and capital saving technical progress,*

1. *A WTR increases the stationary state levels of employment L and the wage rate w. The positive effect of a WTR on employment (resp. hourly wage) is stronger (resp. weaker) when the resource constraint is more stringent: the smaller $F/\underline{\mu}$, the more a WTR creates employment and the less it increases the hourly wage.*

2. *A WTR reduces the total number of hours worked hL and earnings per worker wh. When $F/\underline{\mu}$ is smaller, it decreases hL less and wh more.*

3. *A WTR improves the stationary state level of the lifetime discounted utility of a family.*

Proof.

1. The sign and size of the changes in w and L can be determined using differential calculus. The differential of the ln of (39) with respect to a change in h (evaluated at $\bar{h}$) and L is

$$\frac{dw}{w} = -\frac{dh}{\bar{h}} - \frac{dL}{L}. \tag{40}$$

The differential of the ln of (34) can be written as

$$\frac{dw}{w} = \phi_4 \frac{\ell}{1-\ell}\frac{dL}{L} \quad \text{with} \quad \ell =_{\text{def}} \frac{L}{P} \tag{41}$$

where ℓ is the stationary employment-workforce ratio. The differential of the ln of (31) shows that the relative change in L is linked to the relative changes in Y, w and $\bar{h}$ as follows:

$$\frac{dL}{L} = \frac{dY}{Y} - \frac{dw}{w} - \frac{dh}{\bar{h}}. \tag{42}$$

Introducing the latter expression into (41) gives

$$\frac{dw}{w} = \phi_4 \frac{\ell}{1-\ell}\left[\frac{dY}{Y} - \frac{dw}{w} - \frac{dh}{\bar{h}}\right]. \tag{43}$$

Since a change in h does not affect Y (see (38)), the last equality leads to

$$\frac{dw}{w} = -\frac{\phi_4 \ell}{1-\ell+\phi_4\ell}\frac{dh}{\bar{h}}. \tag{44}$$

Expressions (40) and (44) can also be used to get rid of dw/w, so that:

$$\frac{dL}{L} = -\frac{1-\ell}{1-\ell+\phi_4\ell}\frac{dh}{\bar{h}}. \tag{45}$$

Equations (44) and (45) show that a decrease in h leads to an increase in both w and L. Moreover, (44) shows that the absolute value of the elasticity of w with respect to h is increasing in ℓ, from 0 (when $\ell = 0$) to 1 (when $\ell = 1$); it is also increasing in ϕ_4 at given ℓ. Conversely, (45) shows that the absolute value of the elasticity of L with respect to h is decreasing in ℓ, from 1 (when $\ell = 0$) to 0 (when $\ell = 1$); it is also decreasing in ϕ_4 at given ℓ.

If the resource constraint is more stringent (i.e. if F/μ is smaller), Y and L are smaller (see Proposition 2). So is ℓ, which completes the proof of the first point of the proposition: a WTR creates more jobs and increases less the hourly wage when F/μ is smaller.

2. As a WTR increases employment without affecting output (see (38)), (31) implies that a cut in h is necessarily accompanied by a decline in earnings per worker wh. Since w increases, (31) furthermore implies a reduction in hL. Given the first point of the proposition, the size of the changes in wh and hL depends on the value of ℓ and thereby also that of F/μ as stated in the second point of the proposition. The elasticity of hL to h ranges from 0 when $\ell = 0$ to 1 when $\ell = 1$; that of wh ranges from 1 when $\ell = 0$ to 0 when $\ell = 1$.

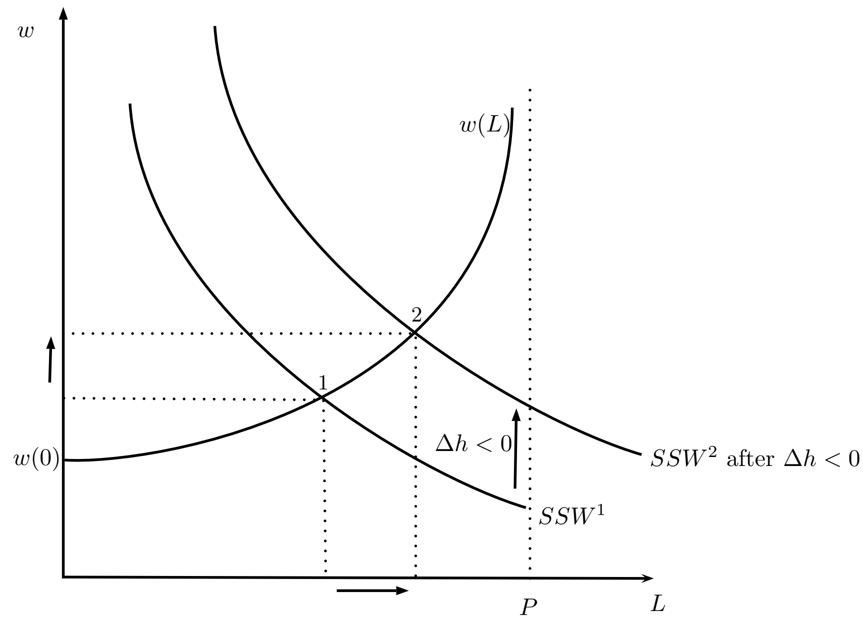
3. At a stationary state equilibrium, the consumption level of (a member of) a family is a bijective function of the aggregate output level. As a WTR does not affect the latter, it let the former unchanged. Therefore, a WTR only changes the stationary lifetime discounted utility of a family through its impact on the disutility of work $d(\bar{h})L$. Since $d(h)$ is increasing and convex in h, a WTR of $x\%$ decreases the disutility per employed family member by more than $x\%$. Given the second point of Proposition 3, it stimulates employment by less than $x\%$. Hence, a WTR decreases $d(h)L$ and unambiguously enhances the stationary state level of the lifetime discounted utility of a family.

■

The positive impact of a WTR on L and w can be graphically illustrated using Figure 1. The wage-setting relationship (34) does not depend on h. As it is easily seen from (39), a WTR implies an increase in w at given L, i.e. an upward shift of the pseudo labour demand SSW. A WTR therefore leads to an increase in w and L as Figure 2 illustrates.

The intuition behind the first point of Proposition 3 is rather simple. When the productivity of human factors grow endlessly, E tends to 1 and the resource and its productivity become the

Figure 2: A WTR raises employment and hourly wage



only limiting factor of output. A WTR then leaves the output level (as well as capital, see (28)) unchanged and leads firms to substitute work hours by other determinants of labour input. They are so pushed to raise wages. For, this stimulates work effort e (see (33)) and is necessary to a higher employment level (see (34)). The positive effect on employment does not prevent the total number of worked hours from decreasing but this decrease is smaller when the resource constraint is more stringent since employment then responds more to the cut in h. The increase in employment is also accompanied by a loss in earnings per worker: in compensation for the cut in h, hourly wage rises but to a lesser extent than the reduction in working hours.

4.3.3 Stationary state with finite resource and bounded technical progress

If all forms of technical progress are bounded (i.e. if η_t is bounded from above by $\bar{\eta} < \infty$ and μ_t is bounded from below by $\underline{\mu} > 0$), the economy is, in the long run, characterised by a stationary state with $E < 1$. Appendix A.4 presents this case more extensively and establishes the following proposition. The proof requires a specification for $B(E_t)$. Henceforth, we suppose that

$$B(E_t) = \frac{1}{1 - E_t}. \tag{46}$$

This specification verifies all the assumptions made when introducing the congestion effect in (6).

Proposition 4 *In a world with a finite resource and bounded technological progress,*

1. *A WTR a) decreases the stationary state level of output but b) all the less so as the resource exploitation rate is high, i.e. as the natural resource is scarce relative to agent inputs;*

2. *A WTR stimulates the stationary state levels of the hourly wage and employment if and only if the resource exploitation rate is high enough, i.e. if the natural resource is scarce enough. In addition, a WTR lowers earnings per worker wh.*

Proof. See Appendix A.4. ■

As far as the impact of a WTR on output and employment is concerned, case 4.3.3 appears as a kind of intermediary situation between the one developed in Subsection 4.2.2 (where the resource constraint is totally relaxed) and the one discussed in Subsection 4.3.2 (where, in the long run, the resource is fully used). If, in this intermediary case, $F/\underline{\mu}$ is increased toward infinity, the resource is not a limiting factor anymore (E tends to 0) and a WTR necessarily decreases output, wage and employment levels as in 4.2.2. If on the contrary, the resource is so scarce that E tends to 1, the resource becomes the only limiting factor of output and a WTR does not impact output at all but raises employment as a result of a substitution between hours on the one hand and employment and effort on the other hand (see the explanation given in 4.3.2).

4.3.4 Discussion of alternative technological assumptions

For modelling simplicity, our model assumes a strict complementarity between agent and resource inputs at a given point in time. Let us however make clear that our results about the (un)employment effect of a WTR are not rooted in this assumption. Any (combination of) assumption(s) that consistently complies with the laws of physics that the marginal productivity of the finite resource is bounded opens the way to a positive employment effect of a WTR. For the sake of illustration, let us consider two alternative assumptions.

First suppose the case of a technology with two embedded Cobb-Douglas functions: final production is described by a Cobb-Douglas function of capital, labour and the resource, the resource extraction technology being itself a Cobb-Douglas function of capital and labour. In this embedded Cobb-Douglas case, all forms of technical progress (resource saving versus labour-and-capital saving) are somehow equivalent in the sense that a labour-capital saving technical progress also increases the productivity of the resource. If the labour-capital saving technical progress went on endlessly, the marginal productivity of the resource would go to infinity. The economy would then admit a balanced growth path even though the resource inflow is finite and a WTR would produce a negative effect on employment as in section 4.2.2. But when Cobb-Douglas functions are assumed, the physical laws which limit the marginal productivity of the resource require to suppose that all forms of technical progress are bounded . In this case, one obtain results equivalent to those of Proposition 4.3.3 in the Cobb Douglas case: a WRT stimulates employment when, in relative terms, the resource is scarce enough.

An intermediary case between our initial assumption and the above-mentioned Cobb-Douglas case is a CES technology between human inputs on the one hand and the resource input on the other hand, with an elasticity of substitution smaller than 1 between the two types of inputs. The two branches of the CES are themselves Cobb-Douglas functions of capital and labour, respectively allocated to final production and to resource extraction. As the elasticity of substitution between human inputs and the resource is smaller than 1, the marginal productivity of the resource remains finite even though the labour and capital saving technical progress is unbounded and the economy tends toward a steady-state as in our Leontief case. With an unbounded (resp. bounded) labour and capital saving technical progress, the employment effect of a WTR could be shown to be qualitatively the same as in Proposition 3 (resp. Proposition 4).

5 Numerical Analysis

In Subsection 5.1, we calibrate the model of the world economy in which the labour-and-capital saving technical progress is unbounded while the resource-saving one is not. In the long-run, it therefore admits a stationary state equilibrium whose properties have been studied in subsection 4.3.1. Subsection 5.2 is devoted to simulations of the dynamics of the modelled economy. First we display and comment the time profile of a range of outcomes in the benchmark environment (i.e. the one that has been calibrated). Next we numerically analyse the transitory dynamics following a

WTR which takes the form of an exogenous permanent shock to the individual duration of working time. The impacts of this policy are also studied in a number of alternatives to the benchmark case where either the natural resource endowment is modified in various ways or the responsiveness of the wage to the unemployment rate varies.

5.1 Calibration of the Model

This subsection explains how initial values of endogenous variables and parameter values are fixed. It is necessary to consider particular functional forms for $U(h_t)$. We assume (see Appendix A.1.2):

$$U(h) = \tilde{\lambda}\, h^{\alpha}\, [1 - \exp(-\xi \cdot h)]^{1-\alpha} \qquad \tilde{\lambda}, \xi > 0, \tag{47}$$

which is a strictly increasing and unbounded function of working time h_t. Under this assumption,

$$h_t \frac{U'(h_t)}{U(h_t)} = \alpha + [1-\alpha] \frac{\xi\, h_t}{\exp(\xi h_t) - 1}, \tag{48}$$

which is decreasing in h_t, from 1 when $h_t \to 0$ to α when $h_t \to +\infty$. The optimal value of $h_t = \bar{h}$ (which verifies (14)) is then the strictly positive root of

$$\exp(\xi \bar{h}) = 1 + \frac{1-\alpha}{1-2\alpha} \xi \bar{h}. \tag{49}$$

For this equation to admit a solution, $1-2\alpha$ must be positive, which implies the restriction $\alpha < 1/2$.

Given specification (47) for $U(h)$, we need to fix parameters $\alpha, \beta, \xi, \tilde{\lambda}, \phi_1, \phi_2, \phi_3, \phi_4, \psi, F$ and δ_R. In addition, assumptions need to be made about the exogenous trajectories of $\{P_t, \eta_t, \mu_t, F_t\}$. A unit of time is assumed to last 15 years. The initial period $t = 0$ covers the years 2000 - 2014. For the world economy, Table 1 summarises the observable initial conditions.

		2000-2014 ($t = 0$)
Y_0 (Trillions 2010USD)	Sum	921.222
Labour force aged 15+ P_0 (persons)	Annual Mean	3,068,093,042
Employment 15+ L_0 (persons)	Annual Mean	2,891,079,080
Productivity Y_0/L_0 (2010USD/head)	Annual Mean	318,643
Unemployment Rate $1-(L_0/P_0)$(%)	Annual Mean	5.77
Savings Rate s (%)	Annual Mean	25

Table 1: Initial conditions (`https://data.worldbank.org/indicator`) and own calculation.

The values of s and Y_0 in Table 1 yield the initial condition K_1. Initial conditions regarding the working hours and labour share at the world level cannot be obtained from the World Bank database and are computed from the Penn World Table (PWT).[22] For 69 countries over 169, PWT provides average working hours. For instance, in 2014, total employment in these 69 countries represented 81% of aggregate employment in the 169 countries. On the basis of this information, we obtain a weighted average working time[23] Hence, since in our model the working time chosen by firms is time-invariant, we have $\bar{h} = 30,930$ hours (over 15 years).

The firms' optimisation under the assumed technology entails that the labour share is $1-\alpha$. The Penn World Table (PWT) computes the labour share for a range of countries. The online appendix of Feenstra et al. [2015] explains the corrections introduced to get what the authors call

[22] See `https://www.rug.nl/ggdc/productivity/pwt/`. We use version 9.0 of the data base.
[23] The weights are the employment share in aggregate employment for the countries where working hours are available. equal to 2062 hours/year for $t = 0$. The order of magnitude we get is compatible with the weekly actual working time values computed by Bick et al. [2018] extrapolated on a yearly basis.

the 'best estimate' labour share. On the basis of 127 country data, the average labour share is equal to 0.52 in 2005, well below the standard 0.66 - 0.7 benchmark range of values (see Feenstra et al., 2015, p. 3178). Under Specification (47), we have seen that the optimality condition (14) can only be solved if one imposes $\alpha < 0.5$. Therefore, given the PWT evidence, we set $\alpha = 0.45$. This choice and the above initial values have several consequences. First, since the model's savings rate $s = \alpha\beta$, combining the observed value of s at time zero (in Table 1) and the chosen value for α yields $\beta = 0,555$ (i.e. a yearly discount rate of 4%). Next, turning to the parameters of $U(h)$, given the values adopted above, the solution to (49) is $\xi = 6.16\,10^{-5}$. Because of the Cobb-Douglas specification, we can normalise $\tilde{\lambda}$ to 1. In addition, since at any time t, $w_t\bar{h} = [1-\alpha]Y_t/L_t$, we deduct that at time 0, the average world hourly wage w_0 amounts to 5.67 2010USD/hour.[24]

Turning to the parameters of (34), notice first that this equality relates the level of the wage rate to the unemployment rate. So, it can be called a "wage curve" (Blanchflower and Oswald, 1994). Wage curves have been estimated in many countries and the finding of a negative correlation of about -0.1 is fairly robust.[25] So, we set ϕ_4 in (34) to 0.1. We later conduct a sensitivity analysis with respect to this parameter. Recall that some constraints have been imposed above on the other parameters appearing in (34), namely: $\phi_1 > \phi_2$, $0 < \psi < 1 - \phi_2/\phi_1$ and $\phi_3 = \phi_1 - \phi_2$. At time 0, given w_0 and the unemployment rate in Table 1, the following equality holds:

$$4.65 = \left[\frac{\phi_1 - \phi_2}{[1-\psi]\phi_1 - \phi_2}\right]^{1/\psi}$$

We arbitrarily set $\psi = 0.25$ and $\phi_2 = 0.1$ (and checked that the simulation results are not much affected by this choice). Then the last equality leads to $\phi_1 = 0.46$, which verifies the inequalities mentioned above. With the chosen value for ψ, this leads to $e_0 = 0.46\, w_0^{0.25} = 0.71$.

Since the natural resource in the model is an abstract aggregate, we interpret variables F_t and X_t as the following measurable aggregate indicators (the next definitions coming from the glossary available at `https://www.footprintnetwork.org/resources/glossary/`):

- F_t is measured by the *Biocapacity*, i.e. "the capacity of ecosystems to regenerate what people demand from those surfaces. (...) Biocapacity is therefore the ecosystems' capacity to produce biological materials used by people and to absorb waste material generated by humans (...) The biocapacity of an area is calculated by multiplying the actual physical area by the yield factor and the appropriate equivalence factor."
- X_t is measured by the *Ecological Footprint*, i.e. "a measure of how much area of biologically productive land and water an individual, population or activity requires to produce all the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management practices."[26]

In accordance with our choice for F_t and X_t, we interpret the unobserved R_t as the *Natural Capital* of the world economy, defined as "the stock of living ecological assets that yield goods and services

[24] To the best of our knowledge, it is hard to find some benchmark information to which this value could be compared. OECD data about average annual wages obviously miss many countries. Some international comparisons of hourly compensation costs in manufacturing are provided by e.g. the US Bureau of Labor Statistics and the Conference Board (see for instance `https://www.conference-board.org/ilcprogram/`). In the manufacturing sector, according to the Conference Board, among ILO economies excluding China and India, the mean hourly compensation amounted to 28 current USD on average over the period 2000-2014. Over the available period 2002-2013, according to the same data source, the average hourly compensation in the manufacturing industry was 1.8 current USD in China and 5.25 in India. Extrapolating these numbers to the world level is not the purpose of this paper.

[25] The wage curve estimations look at the responsiveness of wages of individuals to changing local unemployment rates conditional on a range of other characteristics. See Card [1995] for a critical discussion of the book of Blanchflower and Oswald [1994] and Nijkamp and Poot [2005] and Blanchflower and Oswald [2005] for surveys.

[26] "Global hectares are the accounting unit for the Ecological Footprint and Biocapacity accounts. These productivity weighted biologically productive hectares allow researchers to report both the biocapacity of the earth or a region and the demand on biocapacity (the Ecological Footprint). A global hectare is a biologically productive hectare with world average biological productivity for a given year. Global hectares are needed because different land types have different productivities." (`https://www.footprintnetwork.org/resources/glossary/`). The Global Footprint Network distinguishes five main land types: crop, forest, grazing land, fishing grounds and built-up land.

on a continuous basis. Main functions include resource production (such as fish, timber or cereals), waste assimilation (such as CO_2 absorption or sewage decomposition) and life support services (such as UV protection, biodiversity, water cleansing or climate stability)". As we have no prior information on the depreciation rate of Natural Capital, we set $\delta_R = 0$ in the law of motion (23). Given our theoretical results, it may be seen as a conservative assumption since it does not contribute to intensifying resource scarcity.

The initial values F_0 and X_0 are computed by summing respectively the yearly biocapacity and the yearly ecological footprints over the 2000-2014 period (in billions of global hectares) as measured by the Global Footprint Network. Given this value of X_0 and that of Y_0 in Table 1, we obtain μ_0 as the ratio X_0/Y_0. Making an assumption on the unobserved E_0, (7) then allows us to calculate the initial resource stock R_0 simply as to $\mu_0 Y_0/E_0$. In the reference scenario, we set E_0 to 0.7, which leads to a monotonic convergence of output toward it steady state. A sensitivity analysis will next be proposed, in which a lower E_0 (or equivalently a larger R_0) will be considered.

Data collected by the Global Footprint Network show that the world Biocapacity has been increasing since the sixties. The gain is however declining. Consequently, we assume that starting from the initial value F_{-1} (the sum of the yearly biocapacity taken over the 1985-1999 period), F_t will continue to grow but will reach a finite stationary value F. In the reference scenario, F is set to $1.3\,F_0$ but given the uncertainty on this limit value, a sensitivity analysis will be conducted in the sequel. We assume that F_t is an increasing and concave relationship converging to F, namely:

$$F_t = F + \frac{F_0 - F}{F_{-1} - F}[F_{t-1} - F],\ t \geq 1.$$

For reasons explained in Subsection 3.5, we assume that the resource content per unit of output, μ_t, will continue to shrink toward a strictly positive lower limit $\underline{\mu}$. We assume a 50% scope of gain compared to the initial value μ_0, i.e. $\underline{\mu} = \mu_0/2$. As in the case of F, the uncertainty about this limit value will lead us to conduct a sensitivity analysis with respect to the potential of resource saving technical progress. Computing X_{-1} and Y_{-1} over the years 1985 to 1999 by summing the annual observations for X and Y over these years, we deduct $\mu_{-1} = X_{-1}/Y_{-1}$. The time path of μ_t toward $\underline{\mu}$ is assumed to describe the following declining and convex trajectory:

$$\mu_t = \underline{\mu} + \frac{\mu_0 - \underline{\mu}}{\mu_{-1} - \underline{\mu}}[\mu_{t-1} - \underline{\mu}],\ t \geq 1.$$

As it is standard in the economic growth literature, we assume that η_t increases at an exogenous growth rate g_η: $\eta_t = \eta_0 g_\eta^t, t \geq 1$. In this expression, based on the observed evolution of GDP between period "-1" (covering the years 1985 to 1999) and period 0, we set $g_\eta = 1.084$. η_0 is obtained by solving (27) at time 0.

The exogenous trajectory of the workforce P_t for $t \geq 1$ is based first on the ILO Labour Market Projections.[27] This source provides labour participation rates and size of the labour force estimates in 2016 and 2022 on average in the world. The world average participation rate among the 15+ population declines from 62.1% in 2016 to 61% in 2022. This tendency is assumed to continue because of ageing and the increasing length of education. We set the participation rate at 58% in 2100 and interpolate this rate during the intermediate period. Population Division of the United Nations proposes population predictions until 2100.[28] The evolution of the population aged 15 or more is taken from this source. The size of the workforce is then simply given by the product of the trajectory of this population size and the one assumed for the participation rate. The size of the workforce reaches a plateau around the year 2100 (about 5,371,200 thousands people). We keep the level of the workforce unchanged beyond 2100.

[27]ILO Modelled estimates available in May 2018. See `https://ilostat.ilo.org/data/`.

[28]Probabilistic Population Projections based on the World Population Prospects: The 2017 Revision.

5.2 Simulation Results

Simulations are conducted over the period $t = 1, ..., T = 20$ i.e. from the period 2015-2029 to 2300-2314. The reference scenario, "V0", is illustrated by Figure 3, which shows, for $t \geq 1$, the evolutions of Y_t, L_t, u_t, w_t, X_t, R_t and E_t governed by the system (27)-(33) and the initial conditions. Our comments focus more on qualitative considerations than quantitative ones (e.g. the absolute values reached by output and the unemployment rate). As the main purpose of our simulation exercise is to illustrate the dynamic effects of a WTR and what influences them, the reference scenario (before WTR) first serves as a benchmark in which the evolution of unemployment (higher than at the very beginning of the simulation period) makes the very question of a WTR meaningful.

As the two upper panels of Figure 3 show, V0 is characterised by a monotonic evolution of output (capital) and employment toward their respective steady-state value. This economic growth process is accompanied by a progressive rise of the resource exploitation rate E_t (toward 1 in the case of an unbounded labour-and-capital saving technical progress as explained in Section 4.3.1). This evolution of E_t is the consequence of a steady decline in the resource stock even though the resource saving technical progress leads to a decrease in resource consumption after the first simulation periods (see bottom panels of Figure 3).

Even though the growth potential of the world economy is initially important (World GDP increasing by about 70% over the simulation period), the increase in employment is initially lower than the rise in the labour force and the world unemployment rate thus rises and peaks at a value close to 12% (see middle left panel of 3). Later, as employment keeps on increasing after the stabilisation of the labour force, the unemployment rate decreases and tends toward a value of about 8%, higher than in the first simulation period. Given (34), the non-monotonic evolution of the unemployment rate explains the U-shaped evolution of the hourly wage (see middle right panel of Figure 3) and thus of the individual wage income (as $\bar{h}$ is kept constant by firms).

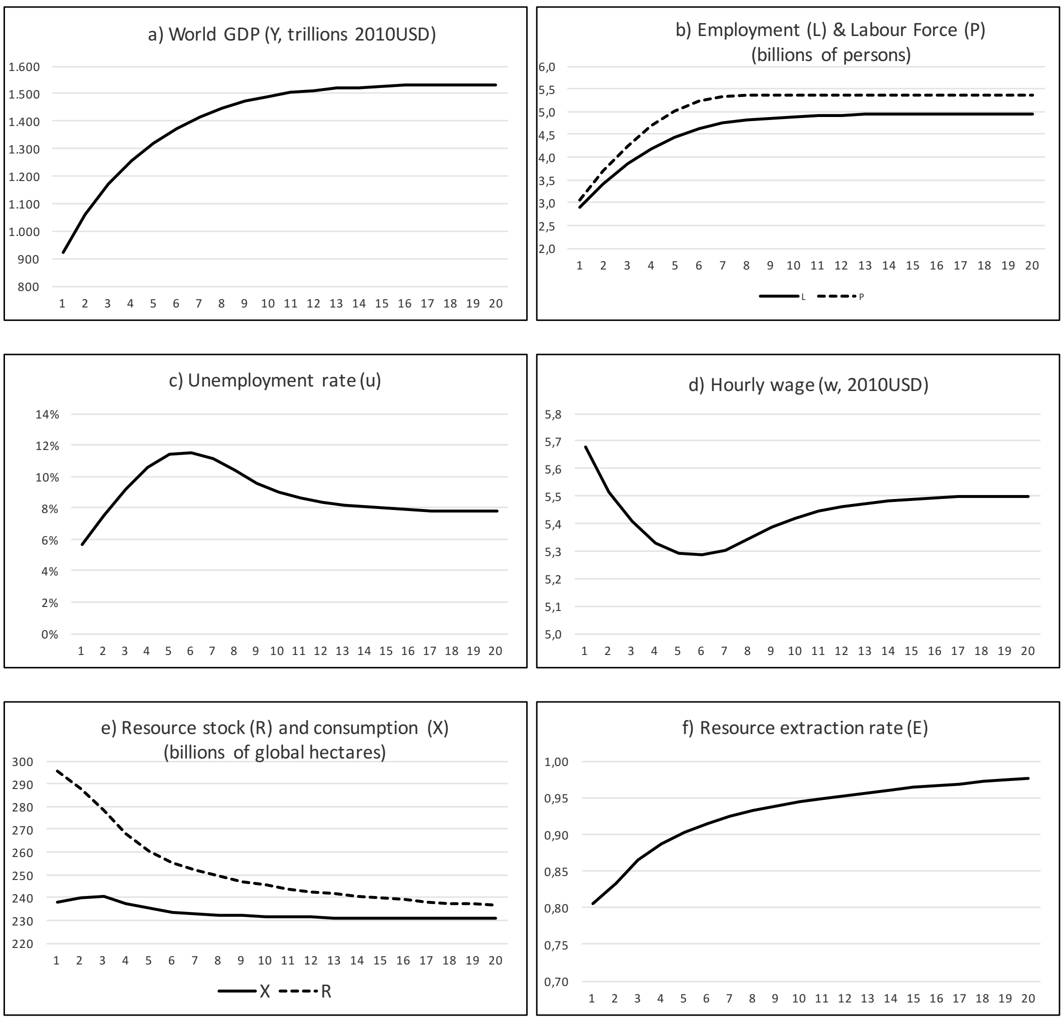
5.2.1 A Working Time Reduction Policy in the reference scenario

Figure 4 illustrates the impact of a WTR equal to 10 % of $\bar{h}$. The simulated model now differs from the reference scenario V0 by preventing firms to minimise costs with respect to hours worked, so that (14) does not apply any more. In the six panels a) to f) of the figure, the continuous line shows the 10 % WTR impact for the calibrated parameters of Scenario V0, the other curve corresponding to a first variant discussed later. Panels 4.a, 4.b, 4.d and 4.e display the percentage change in the variable of interest with respect to the reference scenario without WTR. Panels 4.c and 4.f display the absolute change in u_t and E_t.

When the labour and capital saving technical progress is unbounded while the resource saving one is not, Section 4.3.1 has shown that a WTR has no long run impact on output (Y), the resource exploitation rate (E) and the resource use and stock (X and R). During the transitory dynamics however, output first decreases (Panel 4.a) since the change in the human input mix of firms raises their production cost. Accordingly, the economy first consumes less resource and its stock (Panel 4.e) slightly increases. The resource exploitation rate thus falls and will remain below its value in the reference scenario during the whole transition dynamics (Panel 4.f). This lower E_t contributes to lowering the resource exploitation cost, which progressively compensates the initial cost increase following the cut in h. From period 3 onward, it even allows the economy to reach an output level slightly larger than in the reference scenario during the rest of the transition towards the steady state. Accordingly, from this period onward, the economy consumes more resource after a WTR.

As Panel 4.b (resp. 4.c) illustrates, a WTR has a positive (resp. negative) impact on employment (resp. unemployment) all along the transitory dynamics. The highest gain is achieved after six periods with a rise of aggregate employment of about 5% and a drop in unemployment of almost 5 percentage points. Section 4.3.2 has already explained why the long-run effect of the WTR on employment is positive. But the size of the (un)employment effect of the policy however evolves

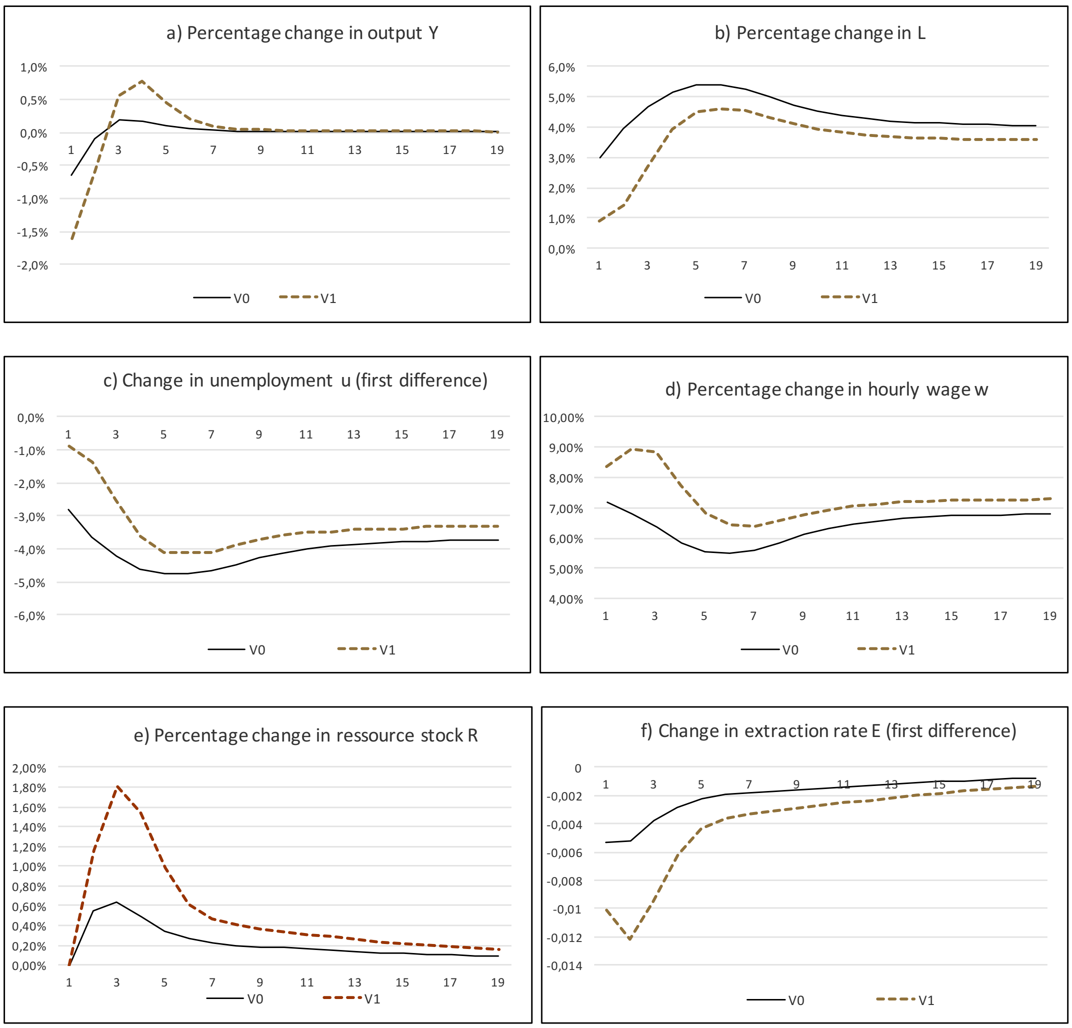
Figure 3: The reference scenario V0 before working time reduction



The simulation period is indicated on the horizontal axis of each panel.

non monotonically. As the comparison between Figures 3 and 4 makes clear, the (un)employment impact of the WTR is the largest during the periods where unemployment peaks in the absence of a WTR; the opposite is true for the hourly wage that the WTR increases more in periods where the employment rate is higher. These observations extend to transitory dynamics the first steady-state property of Proposition 3: a WTR creates more jobs and increases less the hourly wage when the employment rate is lower (or the unemployment rate higher).

Figure 4: Impact of a 10% working time reduction in reference scenario V0 versus V1



Each panel displays the impact of a permanent 10% WTR on the variable of interest in the reference scenario V0 and the alternative scenario V1 where the resource stock is initially more abundant (1.4 greater than in V0).

Given the observed transitory dynamics, the total effect of the WTR on the lifetime discounted utility of a family is a bit less clear-cut than at the stationary state. Two channels are at work: consumption per head and the disutility of work. Consumption per head is proportional to Y_t/P_t. Since the time path for P_t is the same with or without the WTR, only the time path of Y_t matters. Panel 4.a shows that the output effect of the 10% WTR is initially negative but becomes transitorily positive as of the third period. The second channel materialises via the product $d(h_t)L_t$. For the reason already explained in the proof of the third point of Proposition 3, a WTR decreases $d(h_t)L_t$, which enhances the lifetime discounted utility of a family. In sum, a 10% WTR has an ambiguous impact on the instantaneous utility level at the very beginning of its implementation but an unambiguous positive effect later on (a property that remains true even in the limit case where $d(h)$ is uniformly nil).

5.2.2 A Working Time Reduction Policy in alternative scenarios

We now turn to the impacts of a 10% WTR in four alternative scenarios where the value of an initial condition or a parameter is modified. When hours are freely chosen by firms, these four scenarios lead to simulation outcomes different from the reference scenario V0. However, for the sake of brevity, the presentation of the simulations of these variants focuses only on the changes induced by the 10% WTR and compares them to the changes obtained in V0.

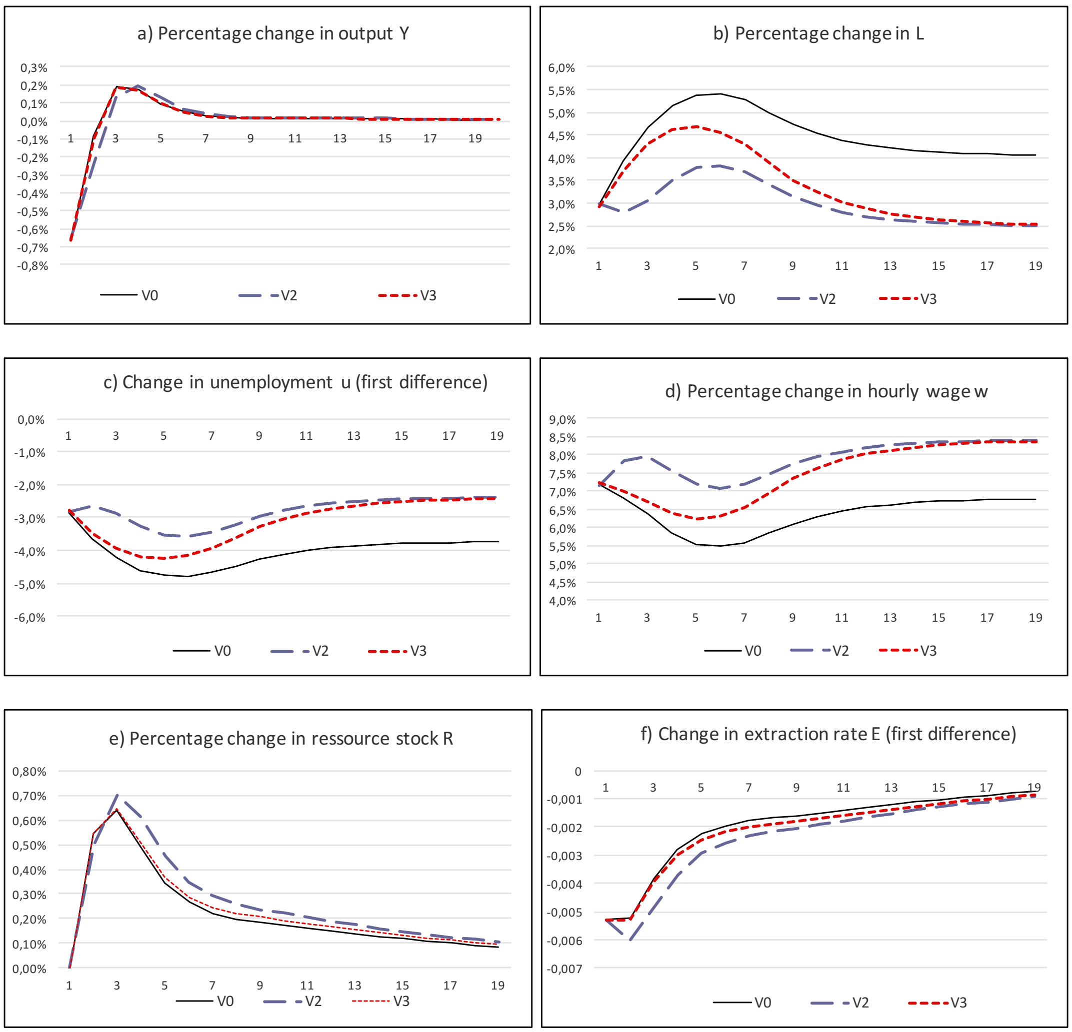
The first alternative scenario V1 (also presented in Figure 4) describes an economy that differs from V0 only by an initial condition, namely: the initial resource stock R_0 is 1.4 times larger in V1 than in V0 so that the initial exploitation rate is lower: $E_0 = 0.5$ in V1 instead of $E_0 = 0.7$ in V0. As the model parameters are identical in V0 and V1, both of them tend toward the same stationary state with identical long-run impacts of a WTR. But the resource remains temporarily more abundant in V1 so that, before the introduction of a WTR, the employment rate is larger in V1 than in V0 during the transitory dynamics. Consequently, the transitory impacts of WTR in V0 and V1 are different. The comparison between V0 and V1 in Figure 4 generalises to transitory dynamics the stationary state result of Proposition 3 regarding the employment and wage effects of a WTR: as the resource is temporarily more abundant and the employment rate higher in V1, the (un)employment effect of the WTR is temporarily much weaker in V1 (Panels 4.b-c): the increase in employment is initially three times larger (+3% versus +1%) in V0 where the resource is relatively scarcer, three quarters of the long run employment impact of the WTR (about + 4%) being reached from the start while it is only one quarter of it in V1. Symmetrically, the 10%-WTR leads to a larger (percentage) change in the hourly wage (Panel 4.d) in V1 than in V0. The initial negative effect of the WTR on output is initially much sharper in V1 (see Panel 4.a) but the subsequent recovery of output is also stronger, the long-run output level remaining unaffected by a WTR (keeping the productivity factor of agent inputs η_t unbounded). As a corollary, the transitory positive effect of the WTR on the resource stock (panel 4.e) is stronger in V1. As time passes, the initial difference in the resource stock between V0 and V1 fades away and the two economies behave more and more similarly.

In the two next variants, labelled V2 and V3, the long-run value of $F/\underline{\mu}$ is 10% larger than in the reference scenario V0: in variant V2, the resource inflow F is increased by 10% with respect to V0; in variant V3, the lower bound for the resource intensity of output $\underline{\mu}$ is decreased by 10% with respect to V0.

The impact of a WTR in V2 and V3 is displayed in Figure 5 and compared to its impact in V0 (continuous line for V0, long dashed blue line for V2, short dashed red line for V3). As $F/\underline{\mu}$ is greater in these variants than in V0, a WTR is now less effective in the long run (see Section 4.3.2 and Panels 5.b-c)). Moreover, since, by construction, the long run ratio $F/\underline{\mu}$ is the same in V2 and V3, they are characterised by the same stationary values of variables Y, K, w, L, e, E and a WTR has identical long-run effects in both variants. The transitory dynamics toward the stationary state however differs: in V2, a greater F improves the availability of the resource from the start; in V3, the trajectory of μ_t toward a lower limit value departs only gradually from its trajectory in V0. Therefore, with regard to the effect of the WTR, the trajectories in V3 initially resemble those observed in V0 but gradually tend towards those observed in V2. As the resource exploitation rate E_t is initially lower in V2 (and will remain so during the transition dynamics as Panel (Panel 5.f) shows), employment (resp. hourly wage) initially increases less (resp. more) in V2 than in V3 but their paths converge toward the same long-run values.

Figure 6 compares the impact of a WTR in the reference scenario (continuous line) and in a fourth variant V4 (dashed and dotted line) wherein parameter ϕ_4 (the elasticity of the wage with

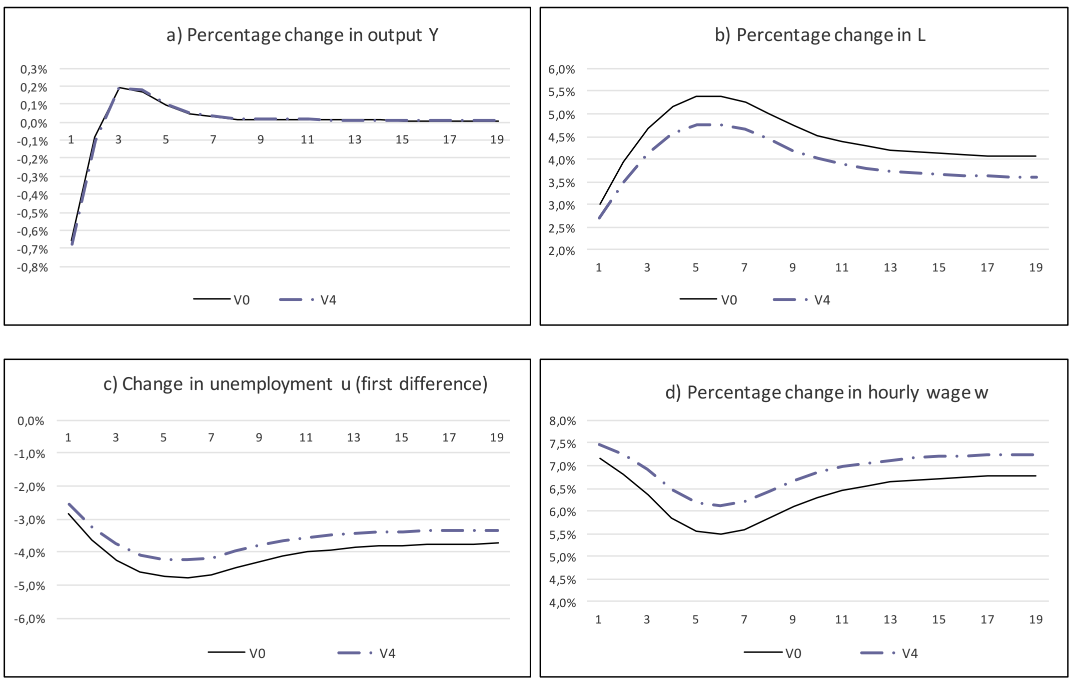
Figure 5: Impact of a 10% working time reduction in reference scenario versus V2 and V3



In scenario V2, the resource inflow F is 10% larger than in scenario V0. In scenario V3, the lower bound for the resource intensity of output $\underline{\mu}$ is 10% smaller than in V0.

respect to the unemployment rate at the macro level (see (34))) is set to 0.12, i.e. above the value of 0.1 in the reference scenario. As the real wage is more responsive to unemployment in V4, the unemployment rate in the *laissez-faire* case where firms set hours is lower than in V0 and peaks at 10.9% (instead of 11.5 in V0). Consequently, the WTR affects (un)employment less in V4 than in V0 (see the first property of Proposition 3 for the stationary state and Panels 6.b-c) for the transitory dynamics); symmetrically, the hourly wage (see Panel 6.d) and thereby the effort at work respond more to the cut in hours in V4 where ϕ_4 and the employment rate are larger (consistently with the stationary state results obtained in (44)). But there is little difference in the response of output (see Panel 6.a), the difference in the evolution of effort compensating that of employment.

Figure 6: Impact of a 10% working time reduction in reference scenario versus V4



In scenario V4, the elasticity of the wage to the unemployment rate is 20% greater than in scenario V0.

6 Conclusion

In a streamlined growth model of a closed (world) economy with an essential renewable resource and unemployment, we have analysed the medium and long-run effects of a working time reduction (WTR). In accordance with the laws of physics, we have assumed that the marginal productivity of the resource is bounded. So is the resource saving technical progress. A WTR always reduces the total number of hours worked and earnings per worker but its impact on (un)employment and the hourly wage crucially depends on the relative scarcity of the resource. If the resource inflow was unlimited, the long run of this economy would be characterised by a balanced growth path. A WTR would then lower the employment and wage levels along this path. When the resource inflow is finite, the economy tends toward a stationary state with a finite output level. If the resource is scarce enough, notably if the technical progress on human factors (labour and capital) is unbounded, a WTR has a favourable effect on employment and on the hourly wage. In the long run, the increase in employment (resp., hourly wage) is larger (resp. smaller) if the resource constraint is tighter, i.e. if the renewable resource inflow is smaller and/or if the resource saving technical progress is more limited. Concomitantly, total hours worked (resp., earnings per worker) decrease less (resp., more) when the resource constraint is tighter. When its effect on employment is positive, a WTR also increases the stationary value of the lifetime discounted utility of workers. Numerical simulations show that our conclusions about the sign and size of effects of a WTR on (un)employment and on the hourly wage hold true along the transitory dynamics.

Our analysis made several simplifications. As far as the implementation of a WTR is concerned, it first ignored that labour skills and tasks are heterogeneous. Therefore, our analysis neglected that the implementation of a WTR becomes more complicate when the costly matching process between workers and jobs is taken into account. Second, we did not distinguish formal from informal firms. In the latter, one can hardly figure out how an authority would impose working time. A WTR only enforced in the formal sector would presumably induce changes in the composition of aggregate output. Such changes would impact employment and wages differently if technologies differ in the formal and informal sectors. Third, demography and participation decisions were taken as exogenous. Since the lifetime discounted utility of labor market participants improves after a WTR (at least in the medium run according to our simulations), a rise in the participation rate could eventually be expected. Then, our quantification of the cut in the unemployment rate should be seen as an upper-bound.

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A Appendix

A.1 Production technology

A.1.1 Functional form for $\mathcal{F}(k_t, l_t, h_t, e_t)$

We consider that a time period is divided in elementary units of time (hours). The pool of workers l_t of a firm consists of λ shifts or teams of $\tilde{l}_t$ workers per hour. The production made by a given shift of $\tilde{l}_t$ workers which operate k_t units of productive capital depends both on the effort level e_t of these workers and on the number of hours they work h_t. Per worked hour in period t, we write the output of the combination $(k_t, \tilde{l}_t)$ as a function of the following type

$$f(k_t, e_t D(h_t)\tilde{l}_t)$$

where $e_t D(h_t)\tilde{l}_t$ represents the total labour input. Function f is strictly increasing and concave in its two arguments and exhibits constant returns to scale in $(k_t, e_t D(h_t)\tilde{l}_t)$. A shift of workers who work h_t hours on productive capital k_t thus produces $h_t f(k_t, e_t D(h_t)\tilde{l}_t)$. If there are $\lambda \geq 1$ shifts of workers (where λ will be considered as exogenous), total output per period is thus equal to:

$$\underbrace{\lambda}_{\text{number of shifts}} \cdot \underbrace{h_t \cdot \underbrace{f(k_t,\, e_t \cdot D(h_t) \cdot \tilde{l}_t)}_{\text{production flow per hour}}}_{\text{production flow per shift of } \tilde{l}_t \text{ workers}} .$$

Under constant returns to scale, this expression can be rewritten as

$$f(\underbrace{\lambda \cdot h_t}_{=_{\text{def}} d(h_t)} \cdot k_t,\, e_t \cdot \underbrace{D(h_t) \cdot h_t}_{=_{\text{def}} \mathcal{D}(h_t)} \cdot \underbrace{\lambda \cdot \tilde{l}_t}_{=_{\text{def}} l_t}).$$

Hence, the total output of a time period can be written as

$$\mathcal{F}(k_t, l_t, h_t, e_t) \quad = \quad f(d(h_t) \cdot k_t, e_t \cdot \mathcal{D}(h_t) \cdot l_t), \tag{50}$$

where function $d(h_t)$ captures the effect of the total working time on the use of capital and $\mathcal{D}(h_t)$ measures the effect of the working hours of a shift of workers on the effective labour units. If we assume that function f is of the Cobb-Douglas type, we can further write

$$\begin{aligned} \mathcal{F}(k_t, l_t, h_t, e_t) &= [d(h_t) \cdot k_t]^\alpha \left[e_t \cdot \mathcal{D}(h_t) \cdot l_t\right]^{1-\alpha} \\ &= U(h_t)\, k_t^\alpha\ [e_t l_t]^{1-\alpha}, \quad \text{where} \quad U(h_t) \equiv [d(h_t)]^\alpha \cdot [\mathcal{D}(h)]^{1-\alpha} \end{aligned} \tag{51}$$

with $U'(h) > 0$.

A.1.2 Functional form for $U(h_t)$ in numerical experiments

In order to obtain a specific functional form for $U(h_t)$, we need to make an assumption on $\mathcal{D}(h_t)$, which captures the effect of worked hours per worker on the effective units of labour used by firms. Several specifications could be used here provided that they guarantee that $U(h)$ is concave (at least) for sufficiently large values of h_t. For the numerical exploration of the model, we opt for the following reduced form:

$$\mathcal{D}(h_t) = A \cdot [1 - \exp[-\xi \cdot h_t]]\,, \quad A,\ \xi > 0$$

where A and η are positive parameters. In this case,

$$U(h_t) = [\lambda \cdot h_t]^\alpha \left[A \cdot [1 - \exp[-\xi \cdot h_t]]\right]^{1-\alpha}$$

which leads to (47) where $\tilde{\lambda} =_{\text{def}} \lambda^\alpha\, A^{1-\alpha}$.

A.2 Cost Minimisation of a Producer of Final Good

Let $\chi_t \geq 0$ be the Lagrangian multiplier associated to constraint (9). The cost minimising problem of a final producer is then equivalent to

$$\min_{\{k_t, l_t, w_t, h_t, \lambda_t\}} \mathcal{L}_t = v_t k_t + w_t h_t l_t + \lambda \left[y_t - \frac{\eta_t}{B(E_t)\mu_t} U(h_t) k_t^\alpha \left[e_t l_t\right]^{1-\alpha}\right]$$

the output level y_t being given. This problem admits the following first-order conditions:

$$\begin{aligned} \frac{\partial \mathcal{L}_t}{\partial k_t} &= v_t - \lambda_t \alpha \frac{y_t}{k_t} = 0 \\ \frac{\partial \mathcal{L}_t}{\partial l_t} &= w_t h_t - \lambda_t [1 - \alpha] \frac{y_t}{l_t} = 0 \\ \frac{\partial \mathcal{L}_t}{\partial w_t} &= w_t h_t - \lambda_t [1 - \alpha] \frac{y_t}{l_t} \frac{w_t}{e_t} \frac{\partial e_t}{\partial w_t} = 0 \quad \text{with} \quad \frac{\partial e_t}{\partial w_t} = \frac{\partial g(w_t, \overline{w}_t, u_t)}{\partial w_t} \\ \frac{\partial \mathcal{L}_t}{\partial h_t} &= w_t l_t - \lambda_t \frac{y_t}{U(h_t)} U'(h_t) = 0 \\ \frac{\partial \mathcal{L}_t}{\partial \lambda_t} &= y_t - \frac{\eta_t}{B(E_t)\mu_t} U(h_t) k_t^\alpha \left[e_t l_t\right]^{1-\alpha} = 0 \end{aligned}$$

The optimality condition on h_t may be rewritten as follows:

$$w_t h_t = \lambda_t \frac{y_t}{l_t} h_t \frac{U'(h_t)}{U(h_t)},$$

which, in combination with the above first-order condition with respect to l_t, leads to (14).Under the assumptions of constant returns-to-scale and a free natural resource, a final firm makes zero profits, which means that the value added by a given output level y_t is shared between labour income and capital rent. With the final good chosen as *numéraire*, one therefore has $v_t k_t + w_t h_t l_t = y_t$. As the sum of the optimality conditions on k_t and l_t leads to $v_t k_t + w_t h_t l_t = \lambda_t\, y_t$, we obtain $\lambda_t = 1$. The optimality conditions can then straightforwardly be rewritten as in the main text.

A.3 Impact of a WTR on BGP trajectories

Using (29), (31), (33) and (35), (29) can be rewritten as

$$\eta_t U(\bar{h}) \left[\alpha\beta Y_{t-1}\right]^{\alpha} \left[\phi_1 w_t^{\psi} \frac{[1-\alpha] Y_t}{w_t \bar{h}}\right]^{1-\alpha} = \mu_t Y_t.$$

By rearranging term, we obtain

$$\frac{\eta_t}{\mu_t} \frac{U(\bar{h})}{\bar{h}^{1-\alpha}} [\alpha\beta]^{\alpha} \left[\phi_1 [1-\alpha]\right]^{1-\alpha} w_t^{[\psi-1][1-\alpha]} = \left[\frac{Y_t}{Y_{t-1}}\right]^{\alpha}.$$

Along a BGP characterised by a constant output growth rate g_Y, one has $Y_t = \exp(g_Y) Y_{t-1}$ and $[Y_t/Y_{t-1}]^{\alpha} = \exp(\alpha g_Y)$. Therefore, the previous equation becomes

$$\frac{\eta_t}{\mu_t} V(\bar{h}) \frac{[\alpha\beta]^{\alpha} \left[\phi_1 [1-\alpha]\right]^{1-\alpha}}{\exp(\alpha g_Y)} = w_t^{[1-\psi][1-\alpha]} \quad \text{where} \quad V(\bar{h}) =_{\text{def}} \frac{U(\bar{h})}{\bar{h}^{1-\alpha}}. \tag{52}$$

As g_Y is independent of $\bar{h}$, (52) shows that a WTR will lead to an increase or a decrease in hourly wage w_t according to whether $V(\cdot)$ is decreasing or increasing at values of h lower than $h = \bar{h}$. Let us determine it by analysing the sign of the elasticity of $V(\cdot)$, which is equal to

$$h \frac{V'(h)}{V(h)} = h \frac{U'(h)}{U(h)} - [1-\alpha]. \tag{53}$$

By condition (14) characterising the choice of h, the elasticity of function V is nil at $h = \bar{h}$:

$$\bar{h} \frac{V'(\bar{h})}{V(\bar{h})} = \bar{h} \frac{U'(\bar{h})}{U(\bar{h})} - [1-\alpha] = 0.$$

Let us consider a finite WTR, $\Delta h < 0$, which decreases h to the value $\bar{h} + \Delta h < \bar{h}$. Under the assumption that the elasticity of function U is decreasing in h, the elasticity of U is larger than $1-\alpha$ for any h in the interval $\left]0, \bar{h}\right[$. Given (53), the elasticity of V is thus strictly positive for any h in the interval $\left]0, \bar{h}\right[$. Consequently, $V(\bar{h} + \Delta h) < V(\bar{h})$ if $\Delta h < 0$. Given (52), a cut in h below $\bar{h}$ thus leads to a decrease in w_t (since we have $1 - \psi > 0$). Via (34), a decrease in w_t also means a decrease in L_t (or an increase in the unemployment rate). Since h (now $= \bar{h} + \Delta h$), w_t and L_t all decrease, (31) implies that Y_t decreases as well. A finite WTR at $h = \bar{h}$ thus lowers the level of the balanced growth path of variables L_t, Y_t, w_t.

A.4 Impact of a WTR on the stationary state when $E < 1$

When η is bounded from above by $\bar{\eta} < +\infty$ and $F/\underline{\mu}$ is finite, the long term of the economy is a stationary state where $E < 1$. At this stationary state, equations (27)-(33) become

$$\bar{\eta} U(\bar{h}) \left[\frac{K}{Y}\right]^{\alpha} \left[e \frac{L}{Y}\right]^{1-\alpha} = \underline{\mu} B(E) \tag{54}$$

$$E = \frac{\underline{\mu} Y}{R} \tag{55}$$

$$\frac{K}{Y} = \alpha\beta \tag{56}$$

$$R = \frac{F - \underline{\mu} Y}{\delta_R} \tag{57}$$

$$\frac{L}{Y} = \frac{1-\alpha}{w\bar{h}} \tag{58}$$

$$e = \frac{\phi_1 - \phi_2}{\psi} w^{\psi} - \frac{\phi_3}{\psi} \left[1 - \frac{L}{P}\right]^{-\psi\phi_4} \tag{59}$$

$$e = \phi_1 w^{\psi}. \tag{60}$$

After substituting K/Y, L/Y and e by (56), (58) and (60), we can rewrite (54) as follows:

$$\overline{\eta}\,[\alpha\beta]^{\alpha}\;U(\bar{h})\left[\frac{\phi_1}{\bar{h}}\frac{1-\alpha}{w^{1-\psi}}\right]^{1-\alpha}=\underline{\mu}B(E).$$

or

$$\mathcal{E}\;\equiv\;w^{[1-\psi][1-\alpha]}=[\alpha\beta]^{\alpha}\,[\phi_1[1-\alpha]]^{1-\alpha}\,\frac{\overline{\eta}}{\underline{\mu}}\,\frac{V(\bar{h})}{B(E)}. \tag{61}$$

where $V(\bar{h})$ has been defined in (52). Moreover, one has (after inserting (57) into (55)),

$$E=E(Y)=_{\text{def}}\delta_R\frac{Y}{F/\underline{\mu}-Y} \tag{62}$$

and $E'(Y)>0$. Since $B'(E)>0$, equality (61) therefore defines, at given $\bar{h}$, a strictly decreasing relationship (labelled $\mathcal{E}$) between Y and w as illustrated in Figure 7. Since $V(h)$ is increasing in h for any $h\in]0,\bar{h}[$, a finite reduction in h implemented from $\bar{h}$ decreases $V(h)$ at the right-hand side of (61). At a given value of Y (and thus E), a reduction in h decreases the value of w given by (61): in the (Y,w) space, a finite $\Delta h<0$ so leads to a downward shift of Curve $\mathcal{E}$.

The increasing wage setting relationship $w(L)$ (see (34)) may be rewritten as an increasing relationship between the wage and the level of output: substituting L by (58) into (34) leads to

$$\mathcal{W}\equiv w=\left[\frac{\phi_3}{(1-\psi)\phi_1-\phi_2}\right]^{1/\psi}\left[1-\frac{1-\alpha}{w\bar{h}}\frac{Y}{P}\right]^{-\phi_4}. \tag{63}$$

At given $\bar{h}$, this equation implicitly defines an increasing relationship (labelled $\mathcal{W}$) between Y and w, as illustrated by Figure 7. At any given $Y>0$, a reduction in h below $\bar{h}$ obviously increases the value of w that verifies (63). Hence, in the (Y,w) space, a lower h leads to a counterclockwise rotation of curve $\mathcal{W}$ around its intercept, as illustrated in Figure 7.

At given $\bar{h}$, relationships $\mathcal{W}$ and $\mathcal{E}$ jointly determine the equilibrium values of Y and w: point 1 on Figure 7 illustrates this equilibrium before WTR. A finite reduction in h produces, as we have seen above, a counterclockwise rotation of $\mathcal{W}$ and a downward shift of $\mathcal{E}$. A WTR therefore has a negative impact on Y, which proves point 1.a) of Proposition 4. But it has an ambiguous effect on w and thereby on L. Point 2 on Figure 7 illustrates the case of a positive impact of a WTR on w.

We now examine more precisely when w will increase after a WTR, which will prove point 2 of Proposition 4 and, finally, point 1.b). Since the changes in $\mathcal{W}$ and $\mathcal{E}$ have opposite effect on w (see Figure 7 again), one needs to determine when the positive wage effect of the change in $\mathcal{W}$ dominates the negative wage effect of the change in $\mathcal{E}$. As Figure 8 shows, it will be the case if *at the initial equilibrium value of* w, the change in Y implied by $\mathcal{W}$ is (in absolute value) larger than the change in Y implied by $\mathcal{E}$ (in absolute value). In the sequel, the former output change is denoted by $\Delta_{\mathcal{W}}Y$ and the latter by $\Delta_{\mathcal{E}}Y$. Since the two are negative numbers,

$$|\Delta_{\mathcal{W}}Y|>|\Delta_{\mathcal{E}}Y|\quad\Leftrightarrow\quad\frac{Y+\Delta_{\mathcal{W}}Y}{Y}<\frac{Y+\Delta_{\mathcal{E}}Y}{Y}, \tag{64}$$

Y being the equilibrium value of output before Δh occurs.

From (63), the output change $\Delta_{\mathcal{W}}Y$ implied by $\Delta h<0$ *at unchanged* w is such that

$$w=\left[\frac{\phi_3}{(1-\psi)\phi_1-\phi_2}\right]^{1/\psi}\left[1-\frac{1-\alpha}{w\left[\bar{h}+\Delta h\right]}\frac{Y+\Delta_{\mathcal{W}}Y}{P}\right]^{-\phi_4}. \tag{65}$$

From the comparison between (63) and (65), we straightforwardly obtain that

$$\frac{Y+\Delta_{\mathcal{W}}Y}{\bar{h}+\Delta h}=\frac{Y}{\bar{h}}\qquad\text{or}\qquad\frac{Y+\Delta_{\mathcal{W}}Y}{Y}=\frac{\bar{h}+\Delta h}{\bar{h}}, \tag{66}$$

Figure 7: Impact of a WTR when $E < 1$

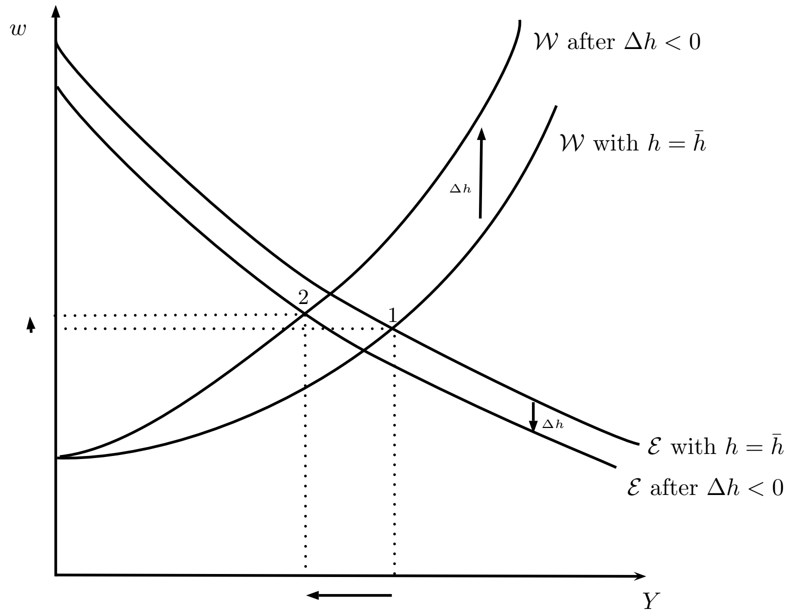
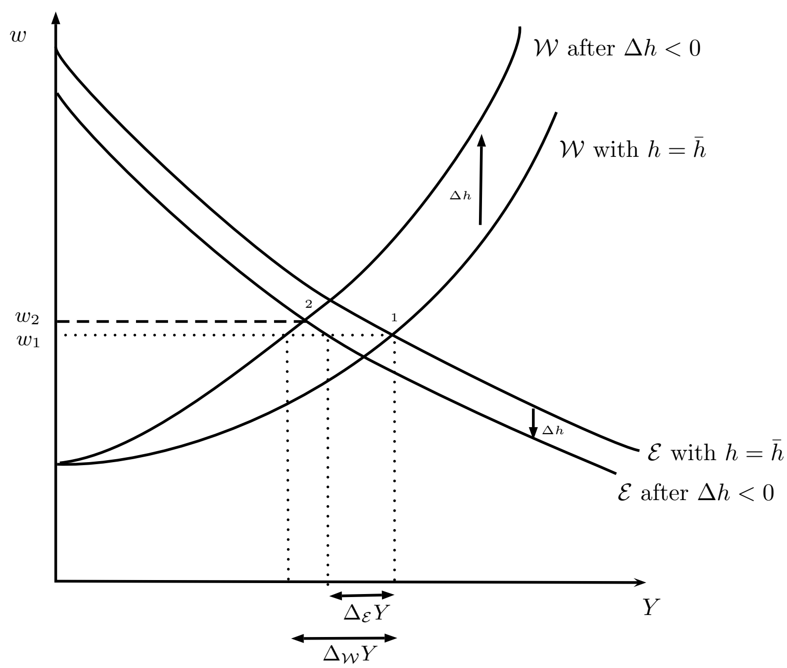


Figure 8: Condition of an increase in w after a WTR when $E < 1$



If $|\Delta_{\mathcal{W}} Y| > |\Delta_{\mathcal{E}} Y|$ at given wage w_1, $\Delta h < 0$ leads to $w_2 > w_1$.

which shows that the size of the change in $\mathcal{W}$ following the cut in h is totally independent of any consideration relating to the scarcity of the resource.

From (61), the output change $\Delta_{\mathcal{E}} Y$ implied by $\Delta h < 0$ *at unchanged* w is such that

$$w^{[1-\psi][1-\alpha]} = [\alpha\beta]^{\alpha} [\phi_1 [1-\alpha]]^{1-\alpha} \frac{\overline{\eta}}{\underline{\mu}} \frac{V(\bar{h}+\Delta h)}{B\left(E\left(Y+\Delta_{\mathcal{E}} Y\right)\right)}. \tag{67}$$

Dividing (67) by (61) gives

$$\frac{V(\bar{h}+\Delta h)}{V(\bar{h})} = \frac{B\left(E(Y+\Delta_{\mathcal{E}} Y)\right)}{B\left(E(Y)\right)}. \tag{68}$$

From (55),

$$\begin{aligned} E(Y+\Delta_{\mathcal{E}} Y) = \underline{\mu}\frac{Y+\Delta_{\mathcal{E}} Y}{R+\Delta_{\mathcal{E}} R} &= \frac{\underline{\mu} Y}{R} \frac{R}{R+\Delta_{\mathcal{E}} R} \frac{Y+\Delta_{\mathcal{E}} Y}{Y} \\ &= E(Y) \frac{R}{R+\Delta_{\mathcal{E}} R} \frac{Y+\Delta_{\mathcal{E}} Y}{Y}, \end{aligned} \tag{69}$$

where, given (57),

$$\Delta_{\mathcal{E}} R = -\frac{\underline{\mu}}{\delta_R} \Delta_{\mathcal{E}} Y > 0$$

because $\Delta_{\mathcal{E}} Y < 0$. Hence the second term at the right-hand-side of (69) lies between 0 and 1:

$$0 < \frac{R}{R+\Delta_{\mathcal{E}} R} < 1. \tag{70}$$

With the functional form (46) chosen for $B(E)$, (68) becomes

$$\frac{V(\bar{h}+\Delta h)}{V(\bar{h})} = \frac{1-E(Y)}{1-E(Y)\dfrac{R}{R+\Delta_{\mathcal{E}} R}\dfrac{Y+\Delta_{\mathcal{E}} Y}{Y}}.$$

Equivalently,

$$1-E(Y)\frac{R}{R+\Delta_{\mathcal{E}} R}\frac{Y+\Delta_{\mathcal{E}} Y}{Y} = [1-E(Y)]\frac{V(\bar{h})}{V(\bar{h}+\Delta h)}$$

or

$$\frac{Y+\Delta_{\mathcal{E}} Y}{Y} = \left[\frac{1}{E(Y)} - \frac{1-E(Y)}{E(Y)} \frac{V(\bar{h})}{V(\bar{h}+\Delta h)}\right] \frac{R+\Delta_{\mathcal{E}} R}{R}, \tag{71}$$

which shows that the size of the change in $\mathcal{E}$ depends, via $E < 1$, on the relative scarcity of the resource. Note that the term between square brackets is smaller than 1 when $\Delta h < 0$, for

$$\frac{1}{E(Y)} - \frac{1-E(Y)}{E(Y)} \frac{V(\bar{h})}{V(\bar{h}+\Delta h)} < 1 \quad \Leftrightarrow [1-E(Y)]\left[1 - \frac{V(\bar{h})}{V(\bar{h}+\Delta h)}\right] < 0,$$

which is necessarily the case: since V is increasing in h over $]0, \bar{h}]$ and $\Delta h < 0$, $V(\bar{h}) > V(\bar{h}+\Delta h)$ and the second term between square brackets in the last inequality is negative. Furthermore, the term in E in (71) is decreasing in E, implying that $\Delta_{\mathcal{E}} Y$ is larger (in absolute value) when E is lower. In other words, the downward shift in $\mathcal{E}$ in response to a WTR is stronger if E is lower. This proves point 1.b) of Proposition 4 because the fall in Y resulting from the shifts in $\mathcal{W}$ and $\mathcal{E}$ will be larger if the downward shift in $\mathcal{E}$ is stronger.

By comparing (66) and (71), we can prove point 2 of Proposition 4. Condition (64) becomes

$$\frac{\bar{h}+\Delta h}{\bar{h}} < \left[\frac{1}{E(Y)} - \frac{1-E(Y)}{E(Y)} \frac{V(\bar{h})}{V(\bar{h}+\Delta h)}\right] \frac{R+\Delta_{\mathcal{E}} R}{R}.$$

Equivalently,

$$\frac{1-E(Y)}{E(Y)}\frac{V(\bar{h})}{V(\bar{h}+\Delta h)} < \frac{1}{E(Y)} - \frac{R}{R+\Delta_{\mathcal{E}}R}\frac{\bar{h}+\Delta h}{\bar{h}}$$

or

$$\frac{V(\bar{h})}{V(\bar{h}+\Delta h)} < \frac{1}{1-E(Y)}\left[1-E(Y)\frac{R}{R+\Delta_{\mathcal{E}}R}\frac{\bar{h}+\Delta h}{\bar{h}}\right]. \tag{72}$$

Given that V is increasing in h over $]0,\bar{h}]$, the left-hand side of this condition is strictly larger than 1 if $\Delta h < 0$. On the right-hand side, the difference between square brackets is necessarily between 0 and 1 if $\Delta h < 0$: The second term of the difference is indeed a product of three positive terms smaller than 1. It is then easy to conclude that when $E = 0$, Condition (72) cannot be verified (the left-hand side being strictly larger than 1 and right-hand side equal to 1). By continuity, it is also the case when E is strictly positive but close enough to 0. At the other extreme, the condition is necessarily verified when $E = 1$ (the right-hand side then tending toward + infinity). By continuity, there thus exists a $\bar{E} \in]0,1[$ such that

$$\begin{aligned} \forall E &\in [0,\bar{E}], \quad \text{condition (72) is not verified and a WTR decreases } w \text{ and } L \\ \forall E &\in]\bar{E},1], \quad \text{condition (72) is verified and a WTR increases } w \text{ and } L. \end{aligned}$$

Earnings per worker wh decreases even when w increases (see (58) where Y is lower).

References

G. Akerlof. Labor contracts as partial gift exchange. *Quarterly Journal of Economics*, 97:543–69, 1982.

C. Anderson. The production process: Inputs and wastes. *Journal of Environmental Economics and Management*, 14(1):1–12, 1987.

M. Andrews, T. Schank, and R. Simmons. Does worksharing work? Some empirical evidence from the IAB-Establishment panel. *Scottish Journal of Political Economy*, 52(2):141–176, 2005.

P. Askenazy. Working time regulation in france from 1996 to 2012. *Cambridge Journal of Economics*, 37:323—347, 2013.

D. Aubert and M. Chiroleu-Assouline. Environmental tax reform and income distribution with imperfect heterogeneous labour markets. *European Economic Review*, 116:60–82, 2019.

S. Baumgärtner. The inada conditions for material resource inputs reconsidered. *Environmental and Resource Economics*, 29:307–322, 2004.

A. Bick, N. Fuchs-Schündeln, and D. Lagakos. How do hours worked vary with income? Cross-country evidence and implications. *American Economic Review*, 108(1):170–199, 2018.

D. Blanchflower and A. Oswald. *The Wage Curve*. MIT Press, 1994.

D. Blanchflower and A. Oswald. The Wage Curve reloaded. NBER Working Papers 11338, NBER, 2005.

A. L. Booth and M. Ravaillon. Employment and length of the working week in a unionized economy in which hours of work influence productivity. *Economic Record*, 69(4):428–436, 1993.

A. L. Booth and F. Schiantarelli. The employment effects of a shorter working week. *Economica*, 54:237–248, 1987.

J. Brandts and G. Charness. Do labour market conditions affect gift exchange? Some experimental evicence. *Economic Journal*, 114(497):684–708, 2004.

P. Cahuc and P. Granier. The consequences of a shorter working time: Some lessons from a general equilibrium analysis. *Recherches Économiques de Louvain / Louvain Economic Review*, 63(1): 13–32, 1997.

L. Calmfors. Work sharing, employment and wages. *European Economic Review*, 27(3):293–309, 1985.

D. Card. The wage curve: A review. *Journal of Economic Literature*, 33(2):785–799, 1995.

M. Chemin and E. Wasmer. Using Alsace-Moselle local laws to build a difference-in-differences estimation strategy of the employment effects of the 35-hour workweek regulation in France. *Journal of Labor economics*, 27:487–524, 2009.

A. Cohn, E. Fehr, and L. Goette. Fair wages and effort provision: Combining evidence from a choice experiment and a field experiment. *Management Science*, 61(8):1777–1794, 2015.

F. Collard and D. de la Croix. Gift exchange and the business cycle: The faire wage strikes back. *Review of Economic Dynamics*, 3:166–193, 2000.

B. Crépon and F. Kramarz. Employed 40 hours or not employed 39: Lessons from the 1982 mandatory reduction of the workweek. *Journal of Polical Economy*, 110(6):1355–1389, 2002.

B. Crépon and F. Kramarz. The two French work-sharing experiments: Employment and productivity effects. In T. Boeri, M. Burda, and F. Kramarz, editors, *Working hours and job sharing in the EU and USA. Are European lazy? Or Americans crazy?* Oxford University Press, Oxford, UK, 2008.

J.-P. Danthine and A. Kurmann. Fair wages in a new keynesian model of the business cycle. *Review of Economic Dynamics*, 7:107–142, 2004.

P. Dasgupta and G. Heal. *Economic Theory and Exhaustible Resources.* Cambridge University Press, 1979.

D. de la Croix, G. de Walque, and R. Wouters. A note on inflation persistence in a fair wage model of the business cycle. *Macroeconomic Dynamics*, 13:673–684, 2009.

J.-F. Fagnart and M. Germain. Quantitative versus qualitative growth with recyclable resource. *Ecological Economics*, 70:929–941, 2011.

R. Feenstra, R. Inklaar, and M. Timmer. The next generation of the Penn world table. *American Economic Review*, 105(10):3150–3182, 2015.

E. Fehr, G. Kirchsteiger, and A. Riedl. Does fairness prevent market clearing? An experimental investigation. *Quarterly Journal of Economics,*, 108(2):437–459, 1993.

U. Gneezy and J. List. Putting behavioral economics to work: Testing for gift exchange in labor markets using field experiments. *Econometrica*, 74(5):1365–1384, 2006.

J. Hassler, P. Krusell, and A.A. Smith. Environmental macroeconomics. In J. Taylor and H. Uhlig, editors, *Handbook of Macroeconomics*, volume 2B, chapter 24, pages 1893–. Elsevier, 2016.

G. Heutel and X. Zhang. Efficiency wages, unemployment, and environmental policy. Discussion Paper 27960, National Bureau of Economic Research, October 2020.

M. Hoel and B. Vale. Effects on unemployment of reducing working time in an economy where firms set wages. *European Economic Review*, 30:1037–1104, 1986.

J. Hunt. Has work-sharing worked in Germany? *Quarterly Journal of Economics*, 114:117–148, 1999.

T. Jackson and P. Victor. Productivity and work in the 'green economy': Some theoretical reflections and empirical tests. *Environmental Innovation and Societal Transitions*, 1:101–108, 2011.

D. Kawaguchi, H. Naito, and I. Yokoyama. Assessing the effects of reducing standard hours: Regression discontinuity evidence from Japan. *Journal of The Japanese and International Economies*, 43:59–76, 2017.

F. Krysiak. Entropy, limits to growth, and the prospects for weak sustainability. *Ecological Economics*, 7(3):182–191, 1985.

R. Layard, S. Nickell, and R. Jackman. *Unemployment : Macroeconomic performance and the labour market*. Oxford University Press, Oxford, 1991.

R. Marimon and F. Zilibotti. Employment and distributional effects of restricting working time. *European Economic Review*, 44:1291–1326, 2000.

G. Meran. Thermodynamic constraints and the use of energy-dependent ces-production functions. a cautionary comment. *Energy Economics*, 81:63–69, 2019.

P. Nijkamp and J. Poot. The last word on the wage curve? *Journal of Economic Surveys*, 19(3): 421–450, 2005.

P. Raposo and J. van Ours. How a reduction of standard working hours affects employment dynamics. *De Economist*, 158(2):193–207, 2010a.

P. Raposo and J. van Ours. How working time reduction affects jobs and wages. *Economics Letters*, 106:61–63, 2010b.

G. Rocheteau. Working time regulation in a search economy with worker moral hazard. *Journal of Public Economics*, 84:387–425, 2002.

R. Sánchez. Do reductions of standard hours affect employment transitions? Evidence from Chile. *Labour Economics*, 20:24–37, 2013.

C. Shapiro and J. Stiglitz. Equilibrium unemployment as a worker discipline device. *American Economic Review*, 74:433–444, 1984.

M. Skuterud. Identifying the potential of work-sharing as a job-creation strategy. *Journal or Labor Economics*, 25:265–287, 2007.

J. Taylor. Work-sharing during the great depression: Did the 'president's reemployment agreement' promote reemployment? *Economica*, 78:133–153, 2011.

P. Victor. Growth, degrowth and climate change: A scenario analysis. *Ecological Economics*, 84: 206–121, 2012.

P. Victor and G. Rosenbluth. Managing without growth. *Ecological Economics*, 61:492–504, 2007.