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Jean-Marie Baland and Kjetil Bjorvatn

Center for Research in the Economics of Development
University of Namur

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Abstract

The privatization of a natural resource is often proposed as a solution to the degradation of natural resources under open access, known as the Tragedy of the Commons. However, this efficiency improvement may come at a distributional cost (Weitzman, 1974) as traditional users of the resource lose income and employment unless they are given a large enough share of the property rights.The present paper demonstrates that, in the case of renewable resources, traditional users may gain from privatization even if they are denied ownership of the resource. Indeed, a private owner maximizes profits by preserving the resource, which results in long-term increases in employment. Hence, the short term losses to traditional users from lower labor demand and loss of rent, must be weighted against the long term gains from employment creation. We also derive the conditions under which privatization is Pareto-improving, benefiting both the new and traditional owners of the natural resource.

Keywords: Renewable resources, Common access; Privatization; Employment creation

JEL-codes: O13; Q23; Q28

1 Introduction

Common access to natural resources, like fish, pastures and trees, is widespread in developing economies and often characterized by excessive exploitation of the resource (see for instance Baland and Platteau, 1996). Motivated by fiscal and environmental concerns, governments seek to restrict access to the commons. This is typically done by privatizing, that is by defining and enforcing exclusive property rights over the resources.

From an efficiency point of view, restricting access to the commons is typically the right thing to do. It is well known that open access may lead to a "tragedy of the commons", characterized by economic loss and environmental degradation. With well defined property rights, profit maximizing behavior leads to the conservation of the resource and thereby improves economic efficiency. However, while privatization of the commons may benefit the economy as a whole, such a transfer of control rights has been shown to necessarily harm labor. Samuelson (1974) and Weitzman (1974) demonstrate that, in the absence of redistribution, workers are always better off with (inefficient) free-access rights than under (efficient) private ownership. This is because privatization restricts the use of a resource, and thereby reduces labor demand and labor incomes. In the words of Weitzman (1974, 234) "....there may be a good reason for propertyless variable factor units to be against efficiency improving moves toward marginalism like the introduction of property rights or tolls unless they get a specific kickback in one form or another." It is also clear that traditional users benefit from privatization if they are given property rights over the resource (see e.g. Roemer and Sylvestre, 1995).

In this paper, we demonstrate that, in the context of renewable resources, privatization necessarily leads to a long-run job creation effect, which is positive for labor. This effect is based on the conservation efforts by the new owner, which leads to a larger future stock of the resource. Conservation thereby implies a short term reduction but a long term increase in labor demand. With the growth of the resource, the long run effect dominates, leading to a net increase in the total demand for labor. As a result, even if traditional users are denied property rights and all the rents are captured by an outsider, they will enjoy an increase in their labor incomes. This increase may be large enough for privatization to be Pareto-improving, even in the absence of redistribution.

By focussing on a static framework, the literature so far has not considered the dynamic impact of privatization in the case of renewable resources, and has thereby ignored its long run conservation properties. A number of contributions, however, extend or revisit the results given by Weitzman, keeping with the traditional, static approach of the commons. For instance, de Meza and Gould (1985) show that when the commons consist of different resources, privatization can increase employment on some of them, even though total employment must fall. In another paper, de Meza and Gould (1987) demonstrate that, if multiple inputs are simultaneously used on the commons, the welfare of traditional users may go up. For example, a well-managed pasture may increase the value of the cattle so much that cattle owners benefit from the privatization of the commons, even though they lost their free access to it. In a similar vein, Brito et al (1997) investigate the case where labor supplied to the resource is not uniformly productive, and show that, under some conditions, labor returns may again rise. Finally, Baland and Francois (2005) show that the commons may effectively protect poor people against adverse income shocks, a property which may be hard to replicate with a privatized resource in the presence of information problems.

To illustrate the potential benefits of restricted access, consider the case of the island of Hispaniola (Diamond, 2005). The two countries that share this island, Haiti and the Dominican Republic, have experienced radical differences in both economic and ecological performance. Despite the geographical and historical similarity between the two countries, per capita income is five times higher in the Dominican Republic than in Haiti. Ecologically, there are also sharp differences, with 28% of the Dominican Republic being forested, compared to only 1% in Haiti. Moreover, the remaining forests of Haiti are continuously being threatened by peasants felling trees for charcoal production.

In Haiti, weak formal institutions and short-sighted policies have led to a de facto open access to the forests, resulting in a tragedy of the commons. In contrast, the Dominican Republic has had for a long time a top-down approach to environmental management, launched under the Trujillo era (1930-61). Trujillo took control over the forests and was personally involved in the forest industry. In the process, he expanded national parks and enforced forest protection, curbing wasteful practices of indiscriminate logging and burning, and prohibiting people from free access to forests. In the long run, this policy has arguably contributed to higher income levels in the population and a sounder ecology.

The paper is organized as follows. Section 2 presents the model, starting with the commons solution and then moving on to the privatized arrangement. Section 3 contains the analysis, comparing labor and total income under the two solutions. Section 4 concludes.

2 The model

Consider an economy consisting of a rural and an urban sector. Production in the rural sector combines labor and a natural resource. We refer to the latter as a forest, with the trees used for charcoal production. The alternative to logging is employment in the city. The price of final goods in both sectors is normalized to unity. In each period t, total labor endowment is unity, allocated between the rural sector (l_{rt}) and the urban sector (l_{ut}):

$$l_{rt} + l_{ut} = 1. \tag{1}$$

Each rural worker works on the commons and cuts one unit of trees. His marginal productivity is equal to 1 if the number of rural workers does not exceed the existing stock of trees, l_{rt}^*. Otherwize, the marginal productivity of additional rural workers falls to zero. Workers in the city receive a wage equal to the value of their marginal product, i.e., $w_t = MP_{ut}$. The marginal product of labor in the city is:

$$w_t = MP_{ut} = 1 - l_{ut} = l_{rt}. \tag{2}$$

There are two periods, and we abstract from discounting. In period 1, the endowment of trees is given by l_{r1}^*. The number of trees in period 2 is determined by the number of trees left in the forest in period 1, $(l_{r1}^* - l_{r1})$, and the growth rate of the forest, g:

$$l_{r2}^* = (l_{r1}^* - l_{r1})(1 + g). \tag{3}$$

We focus on the case where the natural resource is *scarce*, in the sense that, with maximum harvesting in period 1 ($l_{r1} = 1$), there is a not enough of the resource left in period 2 to provide full employment in that sector: $l_{r2} < 1$. This can be expressed as:

$$(l_{r1}^* - 1)(1 + g) < 1 \Rightarrow l_{r1}^* < \frac{2 + g}{1 + g} \equiv l_4, \tag{4}$$

which we assume to hold. We first analyze resource allocation and labor income prevailing under common access before turning to the situation under private property.

2.1 Common access

There are different sources of inefficiency on the commons. Following Hardin (1968), Weitzman (1974) focused on a *static* inefficiency, resulting from crowding externalities in the use of the common resource. In the basic version of our model, we abstract from this static inefficiency and assume that workers exploit the resource as long as their marginal productivity is greater or equal to their alternative occupation. (We discuss further this assumption in Section 3.3.) We focus instead on the *dynamic* externality: traditional users do not internalize the impact of their harvesting decisions on the future stock of the resource. As a result, open access typically leads to overexploitation of the resource in the first period, leaving little or nothing to harvest in the second period, thereby lowering long-term employment opportunities in this sector.

We first consider the case where the resource is relatively scarce and can be fully depleted in the first period, before turning to the case where it is abundant.

2.1.1 Case 1. Relative scarcity of resource

Consider a situation in which the initial resource endowment is small, $l_{r1}^* \leq 1$. The number of loggers is then equal to $l_{r1} = l_{r1}^*$, leading to complete deforestation in the first period. The stock of the resource is nil in the second period. In the first period, the remaining workers, $1 - l_{r1}^*$, work in the city and earn a wage equal to l_{r1}^*, which is lower than the income earned on the resource. The total income of the labour force in the first period is then given by:

$$I_C^1 = l_{r1}^* + (1 - l_{r1}^*)\, l_{r1}^*. \tag{5}$$

Note that the first term in this expression can be defined as the total wage bill, and the second term as the rents enjoyed by the users of the resource. Since there are no trees in period 2, $l_{u2} = 1$: wages and income are nil in period 2.

2.1.2 Case 2. Relative abundance of resource

Consider the situation where $l_{r1}^* > 1$. All workers are involved in logging in period 1. However, due to the abundance of the resource, there are still trees left in period 2. The number of trees in period 2, and hence the number of workers involved in logging in that period, is given by $l_{r2} = l_{r2}^* = (l_{r1}^* - 1)(1+g)$. Wages in period 2 are given by:

$$w_2 = MP_{u2}(l_{r1}^*) = (l_{r1}^* - 1)(1+g). \qquad (6)$$

Total income in this case is given by:

$$I_C^2 = 1 + (l_{r1}^* - 1)(1+g) + [1 - (l_{r1}^* - 1)(1+g)](l_{r1}^* - 1)(1+g). \qquad (7)$$

The first term of I_C^2 is the first period income, which is equal to 1. The second term represents wages and the third term, resource rents in period 2.

2.2 Private ownership

Under private ownership, profit maximization leads to the efficient solution. Without loss of generality, we refer here to a situation where exclusive property rights over the resource have been given to a single owner. His profits are given by:

$$\pi = (1 - w_1)\, l_{r1} + (1 - w_2)(l_{r1}^* - l_{r1})(1+g). \qquad (8)$$

The private owner perfectly internalizes the dynamic externality and fully realizes that his restricting logging in period 1 allows for larger harvests in the second period. The optimal choice combines this conservation incentive with cost minimization, which depends on the wage rates prevailing in each period.

Assuming an interior solution, maximizing profit with respect to l_{r1} yields:

$$1 - w_1 = (1 - w_2)(1+g). \qquad (9)$$

Since $w_1 = l_{r1}$ and $w_2 = l_{r2} = (1+g)(l_{r1}^* - l_{r1})$, we can rewrite (9) as:

$$1 - l_{r1} = (1 - (1+g)(l_{r1}^* - l_{r1}))(1+g). \qquad (10)$$

If growth is sufficiently strong, profit maximization involves a corner solution with full conservation in period 1. We find that:

$$l_{r1} = 0 \Rightarrow l_{r1}^* = \frac{g}{(g+1)^2} \equiv l_0. \qquad (11)$$

For $l_{r1}^* \leq l_0$, the optimal solution leads to $l_{r1} = 0$. From (10), the equilibrium number workers employed in logging in period 1 is given by:

$$\begin{aligned} l_{r1} &= \frac{l_{r1}^* (1+g)^2 - g}{1 + (1+g)^2} \; if \; l_{r1}^* > l_0 \\ l_{r1} &= 0 \; if \; l_{r1}^* \leq l_0. \end{aligned} \tag{12}$$

Given the natural growth of the resource, a profit maximizing agent chooses in period 1 to extract a smaller share of the resource than under the commons. Typically, a profit maximizing agent never depletes the resource in the first period, and the stronger is the growth of the resource, the more is preserved for future extraction. Total labor income when resources are privatized are given by $I_P = l_{r1} + (1+g)(l_{r1}^* - l_{r1})$, where the first term is first period labor income and the second term is second period labor income. Using (12), labour incomes are given by:

$$I_P^1 = \frac{l_{r1}^* (1+g)(2+g) + g^2}{1 + (1+g)^2} \; if \; l_{r1}^* > l_0, \tag{13}$$

$$I_P^2 = (1+g) \, l_{r1}^* \; if \; l_{r1}^* \leq l_0. \tag{14}$$

3 The Analysis

3.1 The effect of privatization on employment and wages

We start the analysis of the model by emphasizing the effect of privatization on employment and wages. We find that:

Proposition 1 *If $g > 0$, second period and total employment in the resource extracting sector is larger under private ownership than under common access.*

Proof. Under common access, period 1 resource extraction is only constrained by the availability of labor. Given $l_{r1}^* < l_4$ in (4), we know that $l_{r1} > l_{r2}$ under common access. In contrast, under private property, $g > 0 \Rightarrow l_{r1} < l_{r2}$. This follows directly from (10). Hence, second period employment is larger under private ownership than under common access. Regarding total employment in the resource extracting sector, we know that

$l_{r1} + l_{r2} = l_{r1} + (1+g)(l^*_{r1} - l_{r1}) = l^*_{r1}(1+g) - gl_{r1}$. Since l_{r1} is higher under common access than private ownership, it follows that with $g > 0$, total employment is higher under private ownership. ■

Regarding wages, we can conclude that:

Proposition 2 *Second period wages and total wages over time are higher under private ownership than under common access.*

Proof. The wage level is a function of employment in the resource extracting sector, more precisely $w_t = l_{rt}$. The proof of Proposition 2 then follows directly from the proof of Proposition 1. ■

In order to determine whether or not privatization is Pareto-improving, the gains in employment and wages to labor must be weighed against the loss by traditional users of their resource rents. In what follows, we analyze more closely this tradeoff.

3.2 When is privatization Pareto-improving?

We now compare labor income in the privatized solution with total income in the commons solution. We first analyze the case of a scarce resource ($l^*_{r1} \leq 1$) and of an interior solution under private property ($l^*_{r1} > l_0$). The critical level of l^*_{r1} for which the two arrangements yield the same level of income to the users is given by:

$$I^1_P = I^1_C \Rightarrow l^*_{r1} = \frac{2 + g(1+g) \pm \sqrt{4(1+g) - 3g^2(1+g)^2}}{2 + 2(1+g)^2} \equiv l_1. \qquad (15)$$

When there is a corner solution under private ownership (i.e., for $l \leq l_0$) , income in the two property regimes is equated when:

$$I^2_P = I^1_C \Rightarrow l^*_{r1} = 1 - g \equiv l_2. \qquad (16)$$

Finally, we compare incomes when the resource is abundant ($l^*_{r1} > 1$). The critical level of the initial endowment of the resource is then given by:

$$I^1_P = I^2_C \Rightarrow l^*_{r1} = \frac{(1+g)(2+g)}{1 + (1+g)^2} \equiv l_3. \qquad (17)$$

We have also defined above l_0 as the critical level of resource endowment below which the profit maximizer chooses not to harvest in the first period, and l_4 as the critical initial endowment above which there is no scarcity of trees under open access in both period. Figure 1 illustrates the critical levels of initial resource endowment as a function of the biological growth rate and indicates which regime gives the higher income to the users, with "P" indicating that private ownership dominates, and "C" that common access dominates. Privatization is necessarily Pareto-improving when private ownership dominates common access, even though traditional users are not directly compensated for the loss of their rights.

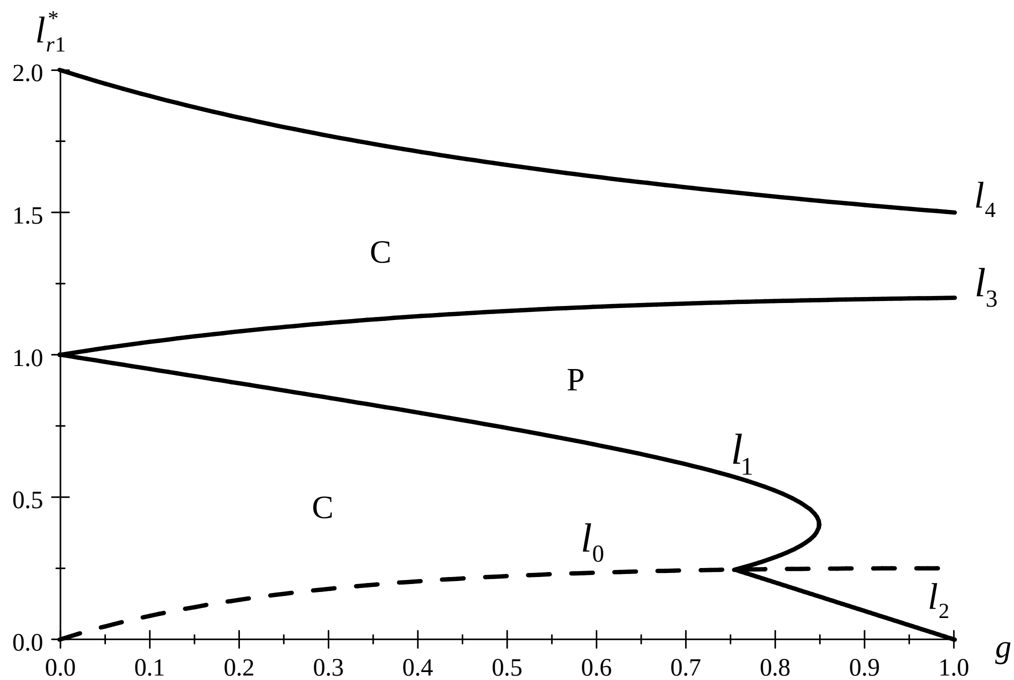

Figure 1: Common access vs Private property

Interpreting the figure, it is useful to start with $g = 0$. We observe that, in this case, workers never benefit from privatization. This is in line with the classical result by Weitzman (1974) discussed in the introduction. There is, however, one level of l^*_{r1} for which workers are indifferent between private ownership and common access; which is $l^*_{r1} = 1$. At this point, the distortion under common access is at its maximal level, with full rent dissipation. The loss in revenue today is then exactly balanced by increased revenues in the future. At $l_{r1}^* = 1$, any positive growth rate naturally makes private ownership the preferred regime for labor. Hence, for $l_{r1}^* = 1$ and $g > 0$, privatization is necessarily Pareto-improving. The range of initial endowments for which private ownership is Pareto-superior to common access increases with g.

Given that the inefficiency of common access is largest at $l_{r1}^* = 1$, changes in the initial resource endowment has a non-monotonic effect on the Pareto-efficiency of privatization. Common access yields a higher income than private ownership either for relatively low or relatively high initial endowments of the natural resource. Intuitively, when l_{r1}^* is small (i.e., to the left of the l_1 and l_2-curves), the resource rents under common access are large in the first period.[1] Privatization of the resource then involves a significant shifting of rents away from the traditional users. Unless the biological growth rate is very high, this results in a loss of income. Similarly, when l_{r1}^* is high (i.e., above the l_3-curve), the rents are large in period 2, and privatization does not lead to a Pareto-improvement. For intermediate levels of l_{r1}^*, however, the rent enjoyed by traditional users under common access is small, and hence the rent shifting effect is dominated by the benefits of employment creation on the resource. In this case, there is no trade off between efficiency and distribution: both arguments support privatization, which is Pareto-improving.

In sum, our analysis demonstrates that, while labor never benefits from privatization in the short term, there is a long term gain. The long term gain is based on the observation that as long as there is a positive growth rate of the natural resource, the period 2 employment in harvesting the resource is bound to be higher under private ownership. The higher the growth rate, the more likely it is that the long term employment effect dominates the short term loss in employment and rents. Moreover, since the rent shifting effect is minimized when the natural resource is "moderately" abundant, this is also the case when the private solution is most likely to benefit labor.

[1] Note that the reason why l_1 reaches a maximum with respect to g around $l_{r1}^* = \frac{1}{2}$ is due to the fact the resource rent under common access is maximized for this level of initial resource endowment. Privatization would in this case lead to a substantial rent transfer, which explains why the growth needed to make labor better off is maximized at this level of initial endowment (in the range of l_{r1}^* and g for which l_1 is the relevant cut off function).

3.3 Discussion

We have assumed so far that the private owners of the resource are price-takers. Actually, privatization of natural resources has often consisted in transferring property rights to a single owner, typically a state company. This may lead to a dominant position on the local labor market, which may affect employment negatively. It is therefore important to discuss the consequences of privatization when the private owner is a monopsonist in the labor market. As a wage setter, the monopsonist understands that $w_1 = l_{r1}$ and $w_2 = l_{r2}$. Modifying the profit function (8), we then have:

$$\pi^m = (1 - l_{r1})\, l_{r1} + (1 - l_{r2})\, l_{r2}. \tag{18}$$

Clearly, the unconstrained choice of the monopsonist is to choose $l_{r1} = l_{r2} = \frac{1}{2} \equiv l_r^m$. This implies that, when the resource is abundant (for $l_{r1}^* > 1$), the monopsonistic owner does not necessarily exhaust all the resources in period 2. Moreover, there is not necessarily growth in the extraction of the natural resource over time. As a consequence, for $l_{r1}^* > 1$, total employment on the resource and labor incomes are always larger under common access than under monopsony. In contrast, when the resource is scarce, the monopsonist optimally expands extraction over time (as is the case with atomistic private owners). Employment thus grows, and total employment is larger than under open access. We therefore have:

Proposition 3 *Total employment in the resource extracting sector is smaller under private monopsony ownership than under common access if and only if* $l_{r1}^* > 1$.

Proof. We define l_0^m as the minimum level of resource endowment which allows the monopsonist to choose $l_{r1} = l_{r2} = \frac{1}{2}$. It is given by:

$$\left(l_{r1}^* - \frac{1}{2}\right)(1+g) = \frac{1}{2} \Rightarrow l_{r1}^* = \frac{(g+2)}{2\,(g+1)} \equiv l_0^m. \tag{19}$$

For $l_{r1}^* < l_0^m$ the natural resource constraint is binding. Using the fact that $l_{r2} = (l_{r1}^* - l_{r1})(1+g)$ in (18) and maximizing with respect to l_{r1}, the equilibrium number of workers in period 1 is given by:

$$l_{r1}^m = \begin{array}{ll} \frac{1}{2} & \text{for} \quad l_{r1}^* \geq l_0^m \\ \frac{l_{r1}^*(1+g)^2 - \left(\frac{1}{2}\right)g}{1+(1+g)^2} & \text{for} \quad l_{r1}^* < l_0^m \end{array}. \tag{20}$$

For $l_{r1}^{*} > 1$, employment under common access is larger than under monopsony. For $l_0^m < l_{r1}^{*} < 1$, the monopsonist chooses $l_{r1}^m = l_{r2}^m = \frac{1}{2}$, whereas employment under common access is equal to l_{r1}^{*} in period 1 and 0 in period 2. Hence, in this case, total employment is higher under monopsony. Finally, for $l_{r1}^{*} < l_0^m$, total employment under monopsony is given by $l_{r1}^m + l_{r2}^m = l_{r1}^m + (l_{r1}^{*} - l_{r1}^m)(1+g)$, with l_{r1}^m defined in (20). It is trivial to show that for $g > 0$, monopsonist employment is strictly higher than common access employment in this case too. Hence, monopsony employment is higher for $l_{r1}^{*} < 1$, while common access employment is higher for $l_{r1}^{*} > 1$. ■

Another important assumption made in this paper is that workers in the resource extracting sector are fully productive, in the sense that their marginal productivity does not fall below that in their alternative occupation. This assumption allowed us to focus exclusively on the dynamic externality involved in the preservation of the resource. This assumption adequately characterizes the case where visible resources are harvested, such as logging in a forest. It also depicts situations under which the rents from the resource are shared among all workers. In other instances, however, rent sharing occurs through employment sharing, where income from the resource is shared exclusively by the users of the resource. Potential users compare the average return of their labor on the resource to the wage rate. As a result, the resource tends to be overcrowded and rents are dissipated. Two effects are at work here. On the one hand, in comparison to the common access situation analyzed above, employment on the resource is larger, and returns to labor are larger. On the other hand, rents are dissipated. Privatization does not necessarily lead to higher total employment in the resource extracting sector. What remains true, however, is the following:

Proposition 4 *Second period employment in the resource extracting sector is larger under private property than under employment sharing common access.*

Proof. With relative scarcity of the resource, $l_{r1}^{*} < 1$, the above observation is trivially true, since with common access the resource is fully extracted in the first period, leaving no basis for employment in this sector in the second period. With relative abundance of the resource, $l_{r1}^{*} \geq 1$, second period employment in the resource extracting sector can be found by equating the average product in that sector with the marginal product in the alternative activity, i..e, $AP_{r2} = MP_{u2}$, which can be stated as

$\frac{\left(l_{r1}^{*}-1\right)(1+g)}{l_{r2}} = l_{r2} \Rightarrow l_{r2}^{s} = \sqrt{\left(l_{r1}^{*}-1\right)(1+g)}$. This second period employment level should be compared with that under private property, which from (??), given $l_{r1}^{*} > l_0$, can be found as $l_{r2} = (1+g)\left(l_{r1}^{*} - \frac{l_{r1}^{*}(1+g)^2 - g}{1+(1+g)^2}\right)$. We find that $l_{r1}^{*} < l_4 \Rightarrow l_{r2}^{s} < l_{r2}$, where l_4 is defined in (12). Hence, as long as there is scarcity of the resource, which we assume is the case, second period employment is necessarily higher under private property than employment sharing common acccess. ■

Hence, privatization leads to a long term gain for labor, even when the traditional institution is characterized by employment sharing. We can therefore conclude that the basic message of our paper, namely that of a long-term gain to labor from privatization, holds true also in this version of the model.

Finally, we have considered in this paper a two period model. This choice was made for simplicity, and in the appendix, we provide an infinite horizon version of the model, in which corresponding results can be derived. Interestingly, private owners always preserve some of the resource and thereby provide positive employment in all periods. It follows that there always exists a positive discount rate below which private property Pareto-dominates common property. Relatedly, we also ignored the role played by discount factors to evaluate the effects on wages and incomes. (The generalized version of the model developed in the appendix explicitly incorporates a discount rate.) The effects of discouting are as expected: larger discount rates lead to less preservation of the resource under private property, thereby reducing future employment gains for the workers. The current values of those gains are also discounted more heavily so that the discounted welfare of the workers under private property is also lower.

4 Concluding remarks

The privatization of natural resources typically restricts access to resources that traditionally have been freely available to local communities. While there are strong efficiency arguments in favor of restricting access and enforcing clearly defined property rights, there are some disturbing distributional effects of this reform. In particular, it has been shown theoretically that, without compensation, labor will necessarily lose. In our paper we focus on renewable resources, and consider the role played by the growth rate of the resource for the distributive impact of privatization. We demonstrate that, while the conservation measures undertaken to maximize profits lead to a short run reduction in employment, they necessarily translate into higher employment in the future. With the growth of the resource, the long run effect dominates, leading to a net increase in the total demand for labor. As a result, even if traditional users are denied property rights and all the rents are captured by an outsider, they will enjoy an increase in their labor incomes. This increase may be large enough for privatization to be Pareto-improving, even in the absence of redistribution.

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5 Appendix: an infinite horizon extension

In an infinite horizon framework, profit maximization implies:

$$1 - w_t = \delta \left(1 + g\right) \left(1 - w_{t+1}\right) \tag{21}$$

where δ represents the discount factor and t the time period. As in the two period model, the technology in the city is such that $w_t = MP_{ut} = 1 - l_{ut} = l_{rt}$, so that equation (21) can be rewritten as:

$$1 - l_{rt} = \delta \left(1 + g\right) \left(1 - l_{rt+1}\right) \tag{22}$$

which can be expressed as:

$$l_{rt+1} = 1 + b^t (l_{r1} - 1) \tag{23}$$

where $b = \frac{1}{\delta(1+g)}$.

In this appendix, we shall focus on the case where $l^*_{r1} \leq 1$, so that the resource can possibly be exhausted during the first period. The extension to large endowments in the resource follow easily at the cost of notational complexity. The biological process of growth of the resource stock, l^*_{rt}, is such that:

$$l^*_{rt+1} = \left(1 + g\right) \left(l^*_{rt} - l_{rt}\right) \tag{24}$$

which can be written as a function of initial stock as subsequent use as:

$$l^*_{rt+1} = l^*_{r1} \left(1 + g\right)^t - \sum_{\tau=1}^{t} l_{r\tau} (1 + g)^\tau. \tag{25}$$

Using equation (23), and using the fact that $\sum_{\tau=1}^{t}(1+g)^{\tau} = \frac{(1+g)^{t+1}-(1+g)}{(1+g)-1}$, we obtain:

$$l^*_{rt+1} = (1+g)^t \left[l^*_{r1} - \frac{(1+g)-(1+g)^{1-t}}{(1+g)-1} - \frac{1+g}{b}\left(l_{r1}-1\right) \frac{\left(\frac{b}{1+g}\right)^{t+1} - \frac{b}{1+g}}{\frac{b}{1+g}-1} \right] \tag{26}$$

In the limit, the transversality condition implies that the resource should be exhausted, that is: $lim_{t\to\infty} l^*_{rt+1} = 0$. Using equation (26), this implies that:

$$l^*_{r1} - \frac{(1+g)}{g} + \frac{(l_{r1}-1)}{\frac{1}{\delta(1+g)^2}-1} = 0 \tag{27}$$

or, equivalently:

$$l_{r1} = 1 + \left(\frac{-1+\delta\left(1+g\right)^2}{\delta\left(1+g\right)^2} \right) \left(l^*_{r1} - \frac{(1+g)}{g} \right) \tag{28}$$

which describes the optimal extraction path in the first period.

Looking to welfare, the discounted utility of a worker under the privatized regime is equal to:

$$U^P = \sum_{t=1}^{\infty} \delta^{t-1} w_t = \sum_{t=1}^{\infty} \delta^{t-1} l_t. \tag{29}$$

Using equations (23) and (28) and rearranging terms, we obtain:

$$U^P = \frac{1}{1-\delta} + \frac{(1+g)}{g} \left(\frac{-1+\delta\left(1+g\right)^2}{\delta\left(1+g\right)^2} \right) \left(l^*_{r1} - \frac{(1+g)}{g} \right), \tag{30}$$

while the discounted welfare of a worker under the commons is equal to

$$U^C = l^*_{r1} + l^*_{r1}\left(1 - l^*_{r1}\right). \tag{31}$$

The welfare impact of privatization can then directly be obtained by comparing U^P and U^C given in the last two expressions. Again, one can easily see that $U^P > U^C$ if l^*_{r1} is close to one, the growth rate of the resource is large or the discount factor is close to one. It is also easy to show that total employment over all periods goes up with privatization, and if the discount rate is low enough ($\delta(1+g) > 1$), the discounted value of the wage rates exceeds that under the commons.