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# Chapter 1

## Sraffa and the environment

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### 1.1 Introduction

In one draft note, Sraffa states that:

“The difference between the ‘Physical real costs’ and the Ricardo–Marxian theory of ‘labour costs’ is that the first does, and the latter does not, include in them the natural resources that are used up in the course of production (such as coal, iron, exhaustion of land) [Air, water, etc. are not used up: as there is an unlimited supply, no subtraction can be made from  $\infty$ ]. This is fundamental because it does away with ‘human energy’ and such metaphysical things. ... But how are we going to replace these natural things? There are three cases: a) they can be reproduced by labour (land properties, with manures etc.); b) they can be substituted by labour (coal by hydroelectric plant: or by spending in research and discovery of new sources and new methods of economising); c) they cannot be either reproduced nor substituted - and in this case they cannot find a place in a theory of continuous production and consumption: they are dynamical facts, i.e. a stock that is being gradually exhausted and cannot be renewed, and must ultimately lead to destruction of the society. But this case does not satisfy our conditions of a society that just manages to keep continuously alive” (Sraffa’s Unpublished Papers and Correspondence, Trinity College Library, Cambridge, UK, as catalogued by Jonathan Smith, D3:12:42: 33, dated 25 March 1946; Sraffa’s emphasis, quoted in Kurz and Salvadori, 2000).

Thus Sraffa states that his theory, the “Physical real costs” theory, is taking into account the natural resources. I argue that this is not true: my position is that

Sraffa is not dealing with natural resources, but with commodities produced by industries and exchanged in the market. Thus all resources which are not produced by industries or which are not exchanged in the market (for instance, wastes) are not encompassed by its model, and can not receive a price.

And we have a confirmation of this when, in chapter XI of his book, Sraffa explicitly introduces natural resources:

“natural resources which are used in production, such as land and mineral deposits, and which being in short supply enable their owners to obtain a rent, can be said to occupy among means of production a position equivalent to that of 'non-basics' among products. Being employed in production, but not themselves produced, they are the converse of commodities which, although produced, are not used in production” (Sraffa, 1960, § 85).

In this chapter, we will see how Sraffa deals with natural resources in his book, through the problematic of the rent, in section 1.2 (after a short introduction about the introduction of the rent in Quesnay and Ricardo's theories). Then we will see how the neo-Ricardians manage to introduce these resources in their models and how they deals with general environmental problems. First we will see the case of exhaustible resources in section 1.3 and then we will study the introduction of waste, the management of pollution control and the exploitation of renewable resources in section 1.4.

## 1.2 Rent

### 1.2.1 Quesnay

Quesnay is one of the firsts to introduce the concept of rent into an economic model: his famous “Tableau Economique” is presented in Versailles in 1758 and reproduced in 1.1). The society is divided in three classes: the productive, the infertile and the aristocratic. The productive class works in agriculture and mines and it is thus exploiting the land. Land is the only factor of production which enables to produce a surplus, i.e. to produce more goods than needed by its exploitation. The productive class produces food products and raw materials and consumes food products. The infertile class is not producing any surplus, it transforms raw materials into manufactured goods and consumes food products. The aristocratic class owns the money, receives the rent from the use of the land, and consumes food products and manufactured goods. Once the period of production is ended, the money is given to the infertile class in exchange for the manufactured goods and to the productive class in exchange for the food products. The infertile class will use the money to pay for the raw materials and the food products. The productive class will then have all the money and will transfer everything to the aristocratic class to pay the rent on the use of the land.

Table 1.1: The Tableau Economique as an input-output table (numbers represent billions) (Pasinetti, 1975)

<i>Entries</i>		<i>Outputs</i>			
		Productive class	Infertile class	Aristocratic class	General sum
Productive class {	- food products	1	1	1	} 5
	- raw materials	1	1	-	
Infertile class		1	-	1	2
Aristocratic class		2	-	-	(2)
General sum		5	2	(2)	7

Represented in the form of table 1.1, the Tableau Economique is an example of a closed Leontief model (Leontief, 1941): the inter-industry sector is represented by the exchanges between the productive and the infertile classes, and the final sector is represented by the aristocratic class. The surplus of the system goes entirely in the hands of the aristocracy: it is represented by the goods owned by the aristocracy at the end of the period of production (third column) and by the added value created and returned to the aristocracy in the

form of rents for the use of land at the end of the period of production (fourth row).

Thus the source of added value comes from the use of the land: this theory of value will be soon replaced by the labor theory of value developed by classical authors (Smith, Ricardo). But this vision of the land as the true source of economic wealth will be taken over in a slightly modified version in the seventies by the tenants of the new “energetics” dogma (Georgescu-Roegen, 1979): these researchers think that energy, instead of land, is the real source of added value and the only primary input of the system of production, as everything could be produced providing that there is enough energy (for a comparison between this vision and Quesnay’s theory, see Burkett, 2003).

### 1.2.2 Ricardo, extensive and intensive rent

At the beginning of the XIX<sup>th</sup> century, Ricardo (1817) build a consistent economic theory, including at the same time a theory of value and a theory of distribution. He develops also his conception of the differential rent: either extensive (when different qualities of one resource are used at the same time in a system of production), or intensive (when different techniques producing the same good are used at the same time). The rent on one process represents the difference between the profitability of this process and the profitability of the least profitable process producing the same good (also called the marginal technique, which does not generate a rent) . The price of the good produced by the different methods is set according to the marginal technique.

This system, this economic theory and this conception of the rent will then be taken over by the neo-Ricardian school.

But Ricardo also assumes some contestable hypothesis: the “law of diminishing returns” (resources of better qualities are used first, as the more profitable techniques) and the absence of technical progress in agriculture, where the theory of differential rent applies. These hypothesis will later, consciously or not, be taken over by marginalist authors, applying intensive rents to all sectors and to all factors of production (see for instance Clark, 1899; Wicksell, 1934).

This abusive expansion of the concept leads to important consequences (Pasinetti, 1999, 2000): on one hand the study of technical progress is abandoned, and on the other hand all factors of production are considered to be scarce, like the factor *land*, and thus a realistic theory of distribution is abandoned via the introduction of the neoclassical function of production (usually of Cobb-Douglas type, Cobb and Douglas, 1928), which is criticized on both theoretical (Robinson, 1954) and empirical (Sylos Labini, 1995) levels.

Sraffa built a proposal able to contradict the neoclassical appropriation of Ricardo, but he nevertheless introduces rent into his theory.

### 1.2.3 Rent and Sraffa

A rent arises as soon as two different processes, with different profitabilities, produce the same good.<sup>1</sup> But in Sraffa's theory, even if there is no equilibrium in terms of demand and supply<sup>2</sup>, it is assumed that the choice of processes is optimal: only the most profitable ones are represented. This allows Sraffa to avoid investigating reasons why two different techniques with different profitabilities are used at the same period of production: this would lead to dynamic analysis of the development of new methods, of the influence of monopolies and dominant positions and into political considerations (for instance old-fashioned techniques may be protected by the government in order to save jobs, or new techniques may be protected so they can grow and be more competitive). This is why the only possible rents to be found in Sraffa's equations are related to absolute scarcity, i.e. related to the presence of a natural resource, which can not be produced.<sup>3,4</sup>

In this case, if the demand for natural resources is high enough (such that even if the natural resource under consideration is renewable, it starts to be depleted), new methods of production have to be introduced in order to satisfy the demand. These new methods may be more or less profitable than the already existing ones, and may or may not use the natural resource. If they are more profitable, Sraffa assumes that they will directly replace the old methods. If they are less profitable, there is the possibility that both new and old methods operate at the same time. This expresses the fact that the natural resource

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<sup>1</sup>This is due to the hypothesis that each commodity can only receive one unique price. This assumption could of course be discussed: when a more profitable technique is introduced, usually the price of the commodity produced by this new technique is lower than the price of the commodity produced by the older technique, in order to attract new consumers.

<sup>2</sup>Supply may differ from the effective demand as prices are not completely equilibrium prices: "this is not proposed as a complete system of equilibrium" (D3/12/46:20, dated 2 April 1957, quoted in Sinha, 2013).

<sup>3</sup>This is not exactly true, as Sraffa also talks about quasi-rents: these rents are earned by owners of machines which are still used even if their allowed life-span is passed. This capital does not appear as a joint-product, but only as an input with no price: the surplus earned because of this non-priced input is the quasi-rent (Sraffa, 1960, § 91).

<sup>4</sup>But then labor is also not produced: could it be that labor becomes a scarce resource? If labor were scarce, it would mean that one process should be added: then, depending on this process, the rent on labor could be calculated (see Abraham-Frois and Berrebi, 1979 on this point). But first this could lead to marginal thinking where all factors of production are scarce (see Lipietz, 1979 on this point). Secondly, Sraffa actually considers briefly, in the beginning of his book, labor as a produced commodity in the "production for subsistence" case. And even if later he chooses to consider wage as an entirely exogenous variable, thus avoiding also such complications, he still thinks that the "necessaries of production" will influence production in the way that labor could be always produced: "we have up to this point regarded wage as consisting of the necessary subsistence of the workers and thus entering the system on the same footing as the fuel for the engines or the feed for the cattle. ... We shall, nevertheless, ... follow the usual practice of treating the whole of the wage as variable. ... Necessaries [of consumption] however are essentially basic and if they are prevented from exerting their influence on prices and profits under that label, they must do so in devious ways (e.g. by setting a limit below which the wage cannot fall; a limit which would itself fall with any improvements in the methods of production of necessaries, carrying with it a rise in the rate of profits and a change in the prices of other products)" (Sraffa, 1960, § 8)..

is scarce, for if it were not scarce, only the most profitable technique would be used: “while the scarcity of land provides the background from which rent arises, the only evidence of this scarcity to be found in the process of production is the duality of methods: if there were no scarcity, only one method, the cheapest, would be used on the land and there could be no rent” Sraffa, 1960, § 88). Sraffa only considers the introduction of less profitable methods using the same natural resource to produce the same good: in this case, they have to be more productive per unit of natural resource than old methods in order to satisfy the demand (an example of the introduction of a less profitable technique not using the natural resource to produce the same good can be found in Erreygers, 2014).

Then, if two methods produce the same good, a rent will arise. This rent can be seized by the owner of the more profitable method, or by the owner of the natural resource.<sup>5</sup> Sraffa considers that the owner of the natural resource receives the rent: the rent is then paid proportionally with the use of the natural resource. As natural resources are not produced, they can not appear in the standard system: they are equivalent of non basic goods in this respect. Thus rents are calculated after the calculation of the rate of profit and the prices of basic commodities<sup>6</sup>. Then Sraffa makes a difference between two type of rents. The first occurs when the natural resource is of different qualities (e.g. in the case of land, lands could have different fertilities). We can call this the extensive rent. The second occurs when the natural resource is homogeneous. We can call this the intensive rent (both terms are not used by Sraffa, who only makes reference to extensive and intensive diminishing returns).

In the case of extensive rent, when different qualities of one natural resource are used, the least profitable quality does not pay any rent. The technique using the no-rent quality is used in order to calculate the price of production and after that, to deduce the different rents (so the natural resource does not appear in the standard system). As it is not possible to know which quality is the least profitable before calculating the prices, each methods have to be tested, the least profitable one being the one which allows to deduce only positive rents. Sraffa takes the example of corn production (coefficient  $k$ ) with  $n$  land of different qualities (Sraffa, 1960, § 86). The  $n$  different methods of production are presented in this way:

$$\begin{aligned}
 (a_{k_1,1}p_1 + a_{k_1,2}p_2 + \dots + a_{k_1,k}p_k + \dots + a_{k_1,m}p_m)(1 + \pi) + l_{k_1}w + \Lambda_1\rho_1 &= b_{k_1}p_k \\
 (a_{k_2,1}p_1 + a_{k_2,2}p_2 + \dots + a_{k_2,k}p_k + \dots + a_{k_2,m}p_m)(1 + \pi) + l_{k_2}w + \Lambda_2\rho_2 &= b_{k_2}p_k \\
 &\vdots \\
 (a_{k_n,1}p_1 + a_{k_n,2}p_2 + \dots + a_{k_n,k}p_k + \dots + a_{k_n,m}p_m)(1 + \pi) + l_{k_n}w + \Lambda_n\rho_n &= b_{k_n}p_k
 \end{aligned}
 \tag{1.1}$$

<sup>5</sup>See section 1.2.5 for an example exploring both possibilities.

<sup>6</sup>And, like with non-basic goods, taxation on rents will not influence the prices of basic goods and the rate of profit: it will only influence the revenue of the rentier.

With  $\Lambda_i$  the given quantity of land of quality  $i$ ,  $\rho_i$  the rent on this land and knowing that  $\prod_{i=1}^n \rho_i = 0$ , because the least profitable land pays no rent.

If the land is homogeneous, intensive rent will arise. Sraffa says that this rent is uniform and is proportional to the amount of natural resource used in production.<sup>7</sup> The two different techniques can be represented in this way, with  $r$  the uniform intensive rent (this representation is from Kurz, 1978 - Sraffa did not propose any algebraic formulation for the calculation of the intensive rent) :

$$\begin{aligned} \mathbf{a}_1 \mathbf{p} (1 + \pi) + l_1 w + \Lambda_1 r &= \mathbf{b}_1 \mathbf{p} \\ \mathbf{a}_2 \mathbf{p} (1 + \pi) + l_2 w + \Lambda_2 r &= \mathbf{b}_2 \mathbf{p} \end{aligned} \quad (1.2)$$

The standard system is constructed knowing that the ratio between input and output of the standard system for each commodity is uniform. With  $q_i$  the multiplier of process  $i$  in the standard system, we must have:

$$\begin{aligned} (q_1 \mathbf{a}_1 + q_2 \mathbf{a}_2) (1 + R) &= q_1 + q_2 \\ q_1 \Lambda_1 + q_2 \Lambda_2 &= 0 \end{aligned} \quad (1.3)$$

Both multipliers will have opposite signs, so the natural resource can be eliminated.<sup>8</sup> We can then calculate the rent, when the prices of basic goods are known:

$$r = \frac{\mathbf{b}_1 \mathbf{p}}{\Lambda_1} \left(1 - \frac{k_1}{\mathbf{b}_1 \mathbf{p}}\right) = \frac{\mathbf{b}_2 \mathbf{p}}{\Lambda_2} \left(1 - \frac{k_2}{\mathbf{b}_1 \mathbf{p}}\right) \quad (1.4)$$

With  $k_i(w) = \mathbf{a}_i \mathbf{p} (1 + \pi) + l_i w$  the cost of inputs of method  $i$ . Thus the method producing more outputs per unit of natural resource must have a bigger cost of inputs per unit of output than the second method, otherwise the rent will be negative: if  $\frac{\mathbf{b}_2}{\Lambda_2} > \frac{\mathbf{b}_1}{\Lambda_1}$ , then it must be that  $\frac{k_2}{\mathbf{b}_2} > \frac{k_1}{\mathbf{b}_1}$  (Sraffa, 1960, § 87, Kurz, 1978).

The first method being the more profitable, if there were no rent, it would be the only one to be used. As demand is more important than what can produce method 1, technique 2 is used: it is more productive (otherwise demand could not be satisfied) but less profitable (otherwise it would replace entirely method 1). Then, in order to calculate the prices, a rent has to be introduced: as it is paid per unit of natural resource used, it impacts both methods in the same way (they become equally profitable).

<sup>7</sup>Bidard (2013) recalls that in Ricardo, the intensive rent is not uniform, in the same manner than the extensive rent: the least profitable method also pays no rent. Ricardo's logic is that the intensive rent arises because the process is intensified on all the homogeneous land: then, with regard with the lands of different quality, an extensive rent and an intensive rent will arise. This is not the same logic in Sraffa as the two methods operate on different parts of the homogeneous land.

<sup>8</sup>If rent is paid before production, we get the same system 1.3: thus I disagree with Lipietz (1979) who thinks that both possibilities lead to different result. The important thing is that the natural resource is eliminated during the construction of the standard system - no matter if rent is a distribution variable or a factor of production: as the standard system only considered basic goods, it must disappear, as labor and non-basic goods.



Both rent, intensive and extensive, can coexist at the same time for a given natural resource and several commodities can use the same scarce natural resource for their production, leading to several different rents (Sraffa, 1960, § 89).

#### 1.2.4 Sraffian rent and dynamics

##### 1.2.4.1 Dynamics and causal relations

Intensive rent is seen as a dynamic phenomena for Sraffa. He thinks that system 1.2 allows for continuous increase in the production of output: if the demand is increasing, method 2 will be more and more used and thus rent will increase, until method 2 is abandoned. Thus there will be a possibility that a new technique more productive but less profitable appears, allowing again for a continuous increase of production (Sraffa, 1960, § 88). It must be noticed than even if the increase of production is continuous, the level of the rent is discontinuous: each time a new technique appears, the level of the rent may increase or decrease suddenly. In all the § 88 paragraph, Sraffa has a dynamic reasoning: he explains why, in a dynamic way, intensive rent appear and how the system can evolve to answer scarcity.

Sinha (2009) writes about the reluctance of Sraffa to take into consideration causal relations, or dynamics, into his theory:

“in a note of 1928 [Sraffa] characterized the theory of value as a ‘geometrical theory’ and its ‘object’ as ‘a photograph of a market place’ where ‘no visible movement takes place’ (PSP D3/12/7, 1928), implying that his propositions do not rest on causal relations, as causal relations can be inferred only when one takes into account time and change. The theme again crops up in another note of 1929 where he tries to distinguish between extensive and intensive rents on the basis of the former being a ‘geometrical’ or ‘timeless’ representation whereas the latter requiring ‘change, or movement: that is to say, we require time’ (PSP D3/12/13:23)”.<sup>9</sup>

When Sinha talks about causality, he means mechanical causality, i.e. a succession of related events, implying temporality and not a logical relation. Indeed, intensive rent require time (i.e. causal explanation) to explain why two methods are jointly used on a homogeneous natural resource, whereas the fact that different qualities of a natural resource exist explains by itself, at a logical level, the different profitabilities, which could lead to the appearance of extensive rents.

Actually, if Sraffa’s system is a real photograph of a market place, it is to be expected that several processes with different profitabilities but producing the same commodity is the rule more than the exception, even if the commodity does not require any natural resources as input. Then, in the latter case, a

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<sup>9</sup>The notes comes from the Wren library, Trinity College, Cambridge.

rule has to be decided on the question of who is earning - or who is paying - the rent: this question can only be answered by looking at dynamic causes (it depends on institutions, power relationships, etc.). Sraffa apparently did not want to introduce such causal explanations in his simple model, and this is why he only talks about the rent on natural resources, and in this case, he states that the rent is earned by the owner of the natural resource.

#### 1.2.4.2 The problem of external rent

A good example of the fact that the real market may be full of rents is the introduction of a new kind of rent by Saucier (1981): the external intensive rent. This rent arises when an increase of demand does not lead to the apparition of a new technique in the sector exploiting the scarce natural resource, but in a sector using as an input the commodity produced by the sector exploiting the natural resource. For instance, let us look at a system producing corn and coal as two basic goods. The corn sector uses land, which is fully cultivated. Now, the demand for coal increases; as the land is fully cultivated, the production of corn can not increase. Thus there is two possibilities: or a new method arises in the corn sector, and if this method is more productive but less profitable, intensive rent will arise; or a new method arises in the coal sector. If the latter method produces more coal per unit of corn, but is less profitable than the previous method, the old and the new method could coexist, and an external intensive rent will arise.<sup>10</sup>

Then a good question is: who will earn this rent? Are we keeping Sraffa's proposal that the owner of the natural resource should earn the rent? Or is it seized by the owner of the most profitable technique in the external sector? The second alternative seems more logical, as it seems difficult for the owners

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<sup>10</sup>This is the right causal reasoning. I disagree for instance with Bidard (2013) who asserts that the apparition of a new method in the coal sector is due to the rise of the corn price, due itself to a rise in demand: "When land is fully cultivated, the price of corn rises and the rent becomes positive". If no different method is introduced in the corn sector, the price of corn will not change (demand changes the level of the production, and thus maybe the methods of production, but do not directly influence prices) and no rent on corn will arise. Similar wrong reasoning can also be found in Salvadori (1983), who introduces the singular rent. She assumes that, if the methods of production are fixed, when the demand will increase a rent will arise on the natural resource. The level of this "singular" rent is set by assuming that there are different effective demands from the different classes of population (workers, rentiers and capitalists).

Actually this false reasoning may have its origin in Ricardo's thinking (Bidard, 2014): "Ricardo stressed that the rise of corn implies that of rents ('Corn is not high because a rent is paid, but a rent is paid because corn is high', Principles, Chapter 2)". So for Ricardo if the demand for corn increases, the price of the corn would increase and a rent could be paid. But for Sraffa, the price of corn could only increase if a new technique, less profitable, is introduced. Thus Bidard is not following a Sraffian reasoning when he states: "The incoming marginal method is the first previously non-operated method which yields the ruling rate of profit when the price of corn rises ... were the rise in the price of corn (and in other prices and rents) smaller than the critical level defined by the law, there would be no incentive to introduce a new method; were it greater, the first method we are considering would yield more than the ruling rate of profit. The level of the rise is therefore the minimum compatible with the introduction of a new method" (Bidard, 2014).

of the natural resources to ask the owners of the coal sector for the rent (see section 1.2.5 on that point).

Furthermore, an other interesting consequences of external rent is that this notion could be further expanded: as soon as there is absolute scarcity, rent can occurs on the sector directly extracting the resource, but also on each sector indirectly using the resource, and all these different rents may arise during the same period of production. Thus by introducing absolute scarcity for one natural resource, if that resource is used to produce basic goods, Sraffa allows the introduction of intensive rents in all sectors.

Then the danger is to fall into the neoclassical logic that the goal if the economic science has to be changed, because all factors of production are scarce:

“from a science that inquires into the nature and causes of the wealth of nations, as it was intended by Adam Smith, [the neoclassical economists] made it ... a science that deals with the use of scarce means to achieve given ends” (Pasinetti, 1999).

In order to avoid this trap, it must be reminded that Sraffa made no assumption on technological progress: new methods may be more productive and more profitable than older ones, and they may not require the same resources as inputs.

#### 1.2.4.3 The order of fertility

The question of the order of fertility is also a dynamic one: in which order the different land, or the different methods, will be introduced when demand will increase? This is a problem of choice of techniques: when demand increase, what is the right criteria to choose the technique to introduce? Ricardo was thinking that the choice of methods depends on the productivity per acres (Bidard, 2013): the criteria of the maximum rate of profit leading to the same choice that criteria of the maximum rate of growth (and Marx was following him on that point, Kurz, 1978). But Sraffa shows that a change in the distribution of the surplus between profits and wages can change this order, by changing the profitability of the different techniques (a little labor intensive method can then be more profitable if the wage increases). Thus the criteria of the maximum rate of profit must be predominant: profitability is more important than productivity, if the demand is satisfied.

Kurz (1978) furthermore shows that the ranking of the land following their profitability is not the same than the order following the rent per acres. Thus a conflict can arise between landowners, seeking for the use of methods leading to high rents, and other classes of population (workers and capitalists): the choice of techniques is actually a political choice.

#### 1.2.5 Sraffian rent and institutions

Sraffa explains the apparition of both rent because of scarcity:

“Natural resources which are used in production, such as land and mineral deposits, and which being in short supply enable their owners to obtain a rent, ... if there were no scarcity, only one method, the cheapest, would be used on the land and there could be no rent” (Sraffa, 1960, § 85 and § 88).

For him, if they were no scarcity, only the most profitable technique would be used on the most profitable land. But actually other causal relation than scarcity can explain the fact that different methods produce the same good with different profitabilities: dominant position, slow propagation of a new technique, slow exploitation of a newly discovered natural resource, governmental protection, etc.

Furthermore Lipietz (1979) warns that if scarcity could be a reason for a rent on natural resources, it is nor a sufficient reason, neither a necessary one. First, if a resource is not scarce, but entirely appropriated by an agent, this agent could establish a false scarcity, by imposing rationing on the use of the resource or by asking for a rent. This kind of rent is not introduced by Sraffa, but is introduced by Marx,<sup>11</sup> who called it “absolute rent”. The level of this absolute rent is not dependent on the existence of two different methods for the exploitation of the natural resources, but only on power relationships (between the owner and the workers on the farm, for instance).<sup>12</sup>

Secondly, if a resource is scarce, the exploitation of the natural resource could still be free. It is only if the resource is privately appropriated that a rent can be asked on the exploitation of the resource. If two methods coexist using an homogeneous natural resource and if one method is more profitable and more productive than the other one,<sup>13</sup> the rent that will arise cannot be paid to the owner of the natural resource, as it would be negative. It would be seized by the most profitable process - the level of the rent is calculated in the same way than for the extensive rent: the marginal method pays no rent. If the method which is more productive is less profitable, Sraffa assumes that the rent is always seized by the owner of the natural resource. But if there is no such owner (or if the owner does not ask for the rent), the rent is also seized by the most profitable process.

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<sup>11</sup>The rent in Marx can originate from (Harribey (2013), p. 82):

1. The different qualities of natural resources, as the ricardian differential extensive rent.
2. The different intensities of production from processes producing the same good, as the ricardian differential intensive rent.
3. The closure to competition (in the case of monopoly or quasi-monopoly), it is then called the absolute rent. This last kind of rent does not appear in Sraffa's model.

<sup>12</sup>In Lipietz terms: “[the level of absolute rent] dépend d'un *rapport de forces*, dans lequel interviennent bien sûr le degré d'organisation du monopole collectif des propriétaires, leur capacité (et celle des locataires) à vivre sans monnayer le droit de propriété, la capacité des différentes classes à nouer des alliances dont la rente est le gage : d'où la lutte des landlords anglais pour maintenir le monopole des blés, d'où les efforts de l'OPEP, etc.” (Lipietz, 1979).

<sup>13</sup>Their existence side by side could be explained by the course of the development of the more profitable technique: it may in future replace the less profitable method, but this has not happened yet (other reasons may be conjured up).

As an example of this last case, let us look at a “corn economy”. Two different methods are used to produce the corn, and they both use homogeneous land. Method 1 is more profitable, but less productive, than method 2:

	<i>Labor</i>	<i>Corn input (ton)</i>	<i>Land (acre)</i>	<i>Corn output (ton)</i>
<i>Method 1</i>	$\frac{1}{2}$	2	2	4
<i>Method 2</i>	$\frac{1}{2}$	2	1	$\frac{7}{2}$

(1.5)

Labor is normalise such as total labor is equal to one, so the wage becomes equal to the value of the share of the surplus given to the workers. There is now two possibilities for the value system: or the rent is seized by the owner or the land, or by the owner of the most profitable process.

In the first case, the value system is represented in this way:

$$\begin{aligned} (1 + \pi) 2p_c + \frac{1}{2}w + 2\rho &= 4p_c \\ (1 + \pi) 2p_c + \frac{1}{2}w + \rho &= \frac{7}{2}p_c \end{aligned} \quad (1.6)$$

With  $\pi$  the rate of profit,  $w$  the wage,  $\rho$  the rent and  $p_c$  the corn price. In order to construct the standard system, both methods has to be multiplied so that the land disappear and total labor stays equal to one:

$$\begin{aligned} 2y_1 + y_2 &= 0 \\ \frac{1}{2}y_1 + \frac{1}{2}y_2 &= 1 \end{aligned} \quad (1.7)$$

With  $y_1$  the multiplier of method 1 and  $y_2$  the multiplier of method 2. We find that  $y_1 = -2$  and  $y_2 = 4$ . Thus the standard system is the following:

$$(1 + \pi) 4p_c + w = 6p_c \quad (1.8)$$

The maximum rate of profit, when the wage is equal to 0, is thus  $R = \frac{1}{2}$ . If the numeraire is the standard commodity, we have:

$$\begin{aligned} 2p_c &= 1 \\ \pi &= R(1 - w) \end{aligned} \quad (1.9)$$

Thus  $p_c = \frac{1}{2}$  and  $\pi = \frac{1}{2}(1 - w)$ . Thus the real value system is now represented like this:

$$\begin{aligned} \left(1 + \frac{1}{2}(1 - w)\right) + \frac{1}{2}w + 2\rho &= 2 \\ \left(1 + \frac{1}{2}(1 - w)\right) + \frac{1}{2}w + \rho &= \frac{7}{4} \end{aligned} \quad (1.10)$$

We find that the rent per acre is equal to  $\frac{1}{4}$ , which means in physical terms  $\frac{1}{2}$  tons of corn per acre; total rent is equal to  $\frac{3}{4}$ , in physical terms  $\frac{3}{2}$  tons.<sup>14</sup>

<sup>14</sup> Using the standard commodity as the numeraire, the rent is independent from distribution; but this ceases to be the case as soon as an other numeraire (for instance  $w = 1$ ) is chosen.

In the second case, the rent is paid to the owner of the most profitable process. The value system is then:<sup>15</sup>

$$\begin{aligned} (1 + \pi) 2p_c + \frac{1}{2}w + \rho &= 4p_c \\ (1 + \pi) 2p_c + \frac{1}{2}w &= \frac{7}{2}p_c \end{aligned} \quad (1.11)$$

In order to construct the standard system, both methods has to be multiplied so that the rent disappears and that total labor stays equal to one:

$$\begin{aligned} y_1 &= 0 \\ \frac{1}{2}y_2 &= 1 \end{aligned} \quad (1.12)$$

We find that  $y_1 = 0$  and  $y_2 = 2$ . Thus the standard system is the following:

$$(1 + \pi) 4p_c + w = 7p_c \quad (1.13)$$

The maximum rate of profit is thus  $R = \frac{3}{4}$ . If the numeraire is the standard commodity, we have:

$$\begin{aligned} 3p_c &= 1 \\ \pi &= R(1 - w) \end{aligned} \quad (1.14)$$

Thus  $p_c = \frac{1}{3}$  and  $\pi = \frac{3}{4}(1 - w)$ . Thus the real value system is now represented like this:

$$\begin{aligned} \left(1 + \frac{3}{4}(1 - w)\right) \frac{2}{3} + \frac{1}{2}w + \rho &= \frac{4}{3} \\ \left(1 + \frac{3}{4}(1 - w)\right) \frac{2}{3} + \frac{1}{2}w &= \frac{7}{6} \end{aligned} \quad (1.15)$$

We find that the (total) rent is equal to  $\frac{1}{6}$ , which means in physical terms  $\frac{1}{2}$  tons.

We thus find that both cases for the distribution of the rent lead to two different systems of value, with two different standard systems, maximum rate of profit, and physical total rents. Then the problem is that when we take a “photograph” of the market place, it is not possible to know how the rent is distributed. In order to know that, one has to investigate the institutions governing the system.

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<sup>15</sup>In such a simple system, we can already know that the first method is the most profitable, and thus that it will seize the rent. In more complex system, we have first to calculate the prices of production: the most profitable process is then the one which, when it is not inserted into the standard system, earns a positive rent.

### 1.3 Exhaustible resources

This section argues that the Hotelling's rule on the rise of royalties during the exhaustion of exhaustible natural resources cannot be retained within a Sraffian framework. At first, a critic of the major attempts that were developed in this domain is conducted. Then this section brings forward the evidence that the value theory is changed by adding the Hotelling's rule<sup>16</sup> and is no longer consistent with Sraffa's thinking. This section also offers an alternative interpretation in which the rise of the rent on exhaustible natural resources is only dependent on technical requirements.

#### 1.3.1 Sraffa and exhaustible resources

As is well known, Sraffa's theory (Sraffa, 1960) of prices deals only with produced commodities. In the case of non-exhaustible natural resources such as land, Sraffa has however shown that rent of land can also be consistently explained by his theory—the existence of rent implies the existence of more than one technique in use to produce a commodity at a moment (see Sraffa, 1960, Ch. 11). In the case of exhaustible natural resources such as oil in the ground, Sraffa (1960), however, remains silent. The silence of Sraffa on the question of how to explain the positive value of exhaustible natural resources has led many neo-Ricardian scholars to introduce Hotelling's rule into Sraffa's theory to fill this gap in his theory. In this section I argue that all such attempts contradict Sraffa's fundamental theoretical position. This should be expected

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<sup>16</sup>In the marginalist paradigm, the concept of natural resources does not exist as all factors of production are seen as scarce, but substitutable, resources: thus there is no specificity of the environment. Natural resources are nevertheless considered as a valid subject of research since the work of Jevons (1865) and HOTELLING (1931). Jevons studies the link between the use of coal, a natural exhaustible resource, and the economic wealth of the United Kingdom: his conclusions were over-pessimistic as he underestimates the importance of technological progress (see Quadrio Curzio and Pellizzari, 1999 on this point). Hotelling tried to find the rate of exploitation of given natural resource such that social well-being is optimised. For him, perfect competition in the market can lead to the emergence of this optimal rate of exploitation (but he was conscious that perfect competition was impossible in the case of the exploitation of real natural resources). Numerous contributions follow these seminal works, concerning the differences in the exploitation of renewable and non-renewable resources, using usually dynamic control and dynamic programming methods. The concept of social well-being is debated; some contributions focus instead on maximisation of private well-being, of the profits, or of the rents that are seized by the owner of the natural resource. Rights and property regimes on natural resources are also discussed (Clark, 1979; Dasgupta and Heal, 1981; Fisher, 1981; Pearce and Turner, 1990).

The general rule, concerning the works following Hotelling research, is that in a situation of perfect competition, the price of the exhaustible natural resource will rise because the selling of the resource should generate the same profit than its conservation. A rent should then be given to the owners of the natural resource if they decide to keep it, and thus the price of the resource increases. This increase in the price  $p_t$  is equal to the uniform rate of profit  $r_t$  of the economy at time  $t$  (Kurz, 2006) :

$$p_{t+1} = p_t (1 + r_t) \tag{1.16}$$

since Hotelling's rule is built on neo-Classical foundations, which does not fit with Sraffa's theoretical foundations. I further go on to provide an alternative explanation for positive value of non-produced exhaustible resources, which I contend is consistent with Sraffa's theoretical foundations. In subsection 1.3.2, I briefly describe the literature that has attempted to introduce Hotelling's rule into Sraffa's theory; in subsection 1.3.3, I show that introduction of Hotelling's rule changes the system of prices in Sraffa's theory; in subsection 1.3.4, I show why these attempts are in contradiction to Sraffa's theoretical foundations; in subsection 1.3.5, I present my alternative explanation, which I think fits with Sraffa's theoretical foundations; in subsection 1.3.6, I present the conclusion of this section.

### 1.3.2 The neo-Ricardian attempts to introduce Hotelling's rule in Sraffa's theory

Before taking up the leading neo-Ricardian attempts to incorporate Hotelling's rule in Sraffa's theory, it may be helpful to take note of the assumptions on which Hotelling's rule is based. These assumptions are: the exhaustible resource is privately owned; the owner wants to maximize the present value of his future profits; the market rate of interest  $\gamma$  expresses the average degree of impatience in the economy and it is equal to the society's rate of time preference; there is perfect competition;<sup>17</sup> the quality of the resource is uniform and constant at any time; the stock of the underground natural resource is known; there is perfect foresight with respect to demand for the resource; it is possible to calculate the present social value of the resource, i.e. the total value enjoyed in present and future periods by the consumers of the resource; and finally, quantity produced and price  $p(t)$  depend on demand and supply functions of the resource. Given these assumptions, the resource price that maximizes the present social value, when there is no extraction cost, is given by:  $p(t) = p(0) e^{\gamma t}$ . This is the price of the resource in the ground, also called 'scarcity rent' (e.g. in Solow, 1974) or 'royalty' (e.g. in Devarajan and Fisher, 1981). This royalty should be added to the extraction cost in order to find the price of the extractible resource.

In this paper we do not take up the problems with Hotelling's rule itself.<sup>18</sup> Here we focus only on the reasons why it is not correct to integrate Hotelling's rule inside Sraffa's framework. Among the major contributors in this area are Kurz and Salvadori (Kurz and Salvadori, 1997, 2000, 2001, 2009), Schefold (Schefold, 1989, 2001), Bidard and Erreygers (Bidard and Erreygers, 2001a,b) and Parrinello (Parrinello, 1983, 2001, 2004)<sup>19</sup>. Kurz and Salvadori ask the

<sup>17</sup>This assumption is later relaxed in Hotelling's model, but this is never done in the following neo-Ricardian models.

<sup>18</sup>There could be first an empirical criticism about the reality of this rule. Some empirical facts are not taken into account (market imperfections, difference in ore qualities, capacity and investment constraints, exploration costs, e.g. see Krautkraemer, 1998) and empirical analyses of price do not always reflect the Hotelling's rule (e.g. see Hart and Spiro, 2011).

<sup>19</sup>We could also add to this list Ravagnani (2008) who criticizes both backstop technology



question: “why the owners of such [exhaustible] resources do not sell the whole amount that they own at current prices in order to invest the proceeds in an industry where the normal rate of profit can be obtained” (Kurz and Salvadori, 1997). Their answer is: “the storage of natural resources, which may be considered as a ‘conservation industry’, cannot be operated if it does not yield a ‘royalty’ to the owners of the resources” (Kurz and Salvadori, 1997). They justify this precisely because they assume a long-term *equilibrium* framework: “Hotelling’s rule [see Hotelling (1931)] is nothing but the application of the concept of a uniform rate of profit to all processes in the economy, whether these are conservation or production processes” (Kurz and Salvadori, 2001). Thus Kurz and Salvadori develop a dynamic Input-Output model under the assumption of free competition (uniform rate of profit), constant returns to scale and a given real wage rate where the Hotelling’s rule applies.

For Bidard and Erreygers: “a consistent theory of exhaustible resources is needed just as much as a consistent theory of prices” (Bidard and Erreygers, 2001a). They accept Hotelling’s rule and apply it in the Sraffian framework without providing any justification:

“In order of analytical complexity, the question of exhaustible resources comes next to that of land with, however, a qualitative gap: the price of an exhaustible resource changes with time, in order to compensate his owner for waiting (Hotelling’s rule)” (Bidard and Erreygers, 2001a).

They acknowledge that the Hotelling’s rule may be based on weak empirical basis, but they only care about theoretical consistency. They work with a small system with one commodity and one exhaustible natural resource, with no extraction cost and constant returns to scale. In my view their model has been successfully generalised by Schefold (Schefold, 2001).

Schefold (Schefold, 1989, 2001) is ambiguous on the use of Hotelling’s rule in a Sraffian framework. On the one hand, he thinks that Ricardo’s theory of rent can be applied to “the extraction of most exhaustible resources” (Schefold, 2001) and rightly finds that the assumptions behind the Hotelling’s rule (perfect foresight on future demand, technology and stocks) are not compatible with a Classical framework if the natural resource is a basic good:

“if the resource really gets exhausted over an intermediate time span, its price must rise; if it is a basic commodity, relative prices

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models supposing perfect foresight (models of the type of Kurz and Salvadori, 2000; Bidard and Erreygers, 2001a; Schefold, 2001), and intensive rent models making strong assumptions on the existence of a second process at each period of time allowing to calculate the rent (models of the type of Parrinello, 2001). He shows that in the case of oil industry in the US, contracts between managers and owners do not show that royalties are increasing following the rate of profit: they are actually highly dependent on norms, previously created through bargaining and power relationships. These norms can be broken when power relationships change and, in case of State ownerships, royalties depend on public policy and international relationships. So he argues that royalties should be considered as an exogenous variable, on the same ground than the profit rate (or the wage rate).

of other commodities must change, complicated patterns of substitution in the processes of production and of consumption may ensue in all other periods and perfect foresight becomes implausible” (Schefold, 2001).

However, on the other hand, while playing “the game of logic and [trying] to reconstruct a theory of exhaustible resources within the context of classical theory”, Schefold assumes that “the rise of the price of the exhaustible resource, in the absence of technical progress, is the expression of a future diminution of the surplus available for consumption and investment” (Schefold, 2001). He also justifies this assumption on the ground that “a classical model is a long period model” (Schefold, 2001). He then constructs a model with constant returns to scale, an exhaustible resource (which could be a basic commodity) and the Hotelling’s rule on the price of the resource in the ground (i.e. before extraction).

Parrinello (Parrinello, 1983, 2001, 2004) follows an interesting approach: the royalty in his case is equivalent to an intensive rent, whereas for other neo-Ricardians the royalty is seen as the profit of the conservation process. Furthermore, instead of assuming first that the royalty increases and then looking at the consequences on quantities (as in the first three models), he assumes that quantities are given and then looks at its consequence on the royalty. But then how is it possible to face the contradiction that the royalty should follow the Hotelling’s rule? In fact, for Parrinello, Sraffa’s system of production “is assumed to be the result of profit maximizing choices under conditions of competition and long period equilibrium” (Parrinello, 2004).

He follows here the interpretation of Garegnani (1976) that a process of gravitation is able to generate a uniform rate of profit and a choice of technique such that the system of production is square. But this process of gravitation is seriously questioned by Sinha and Dupertuis (2009). Furthermore, there is no reason to accept a priori that there is “competition and profit seeking behavior” (Parrinello, 2004), because the uniformity of the rate of profit is deduced from the equations of the system of production (Sinha, 2012). So from my point of view, Parrinello’s model is good (no assumption regarding constant returns to scale, no price on the resource not yet extracted) but there is no need to justify the Hotelling’s rule with it. I will now concentrate my criticism on the first three models in subsections 1.3.3 and 1.3.4, before presenting a modified version of Parrinello’s model in subsection 1.3.5.

### 1.3.3 Introducing Hotelling’s rule inside Sraffa changes the price system

Let us start with Kurz and Salvadori’s model, which does not include rent (Kurz and Salvadori, 2000).

There are  $n$  commodities, and  $m > n$  processes operating with constant returns to scale. The price column vector during the period of production  $t$  is written  $\mathbf{p}_t$  and the line activity vector (describing the scale of operation for

each process) is written  $\mathbf{x}_t$ . The quantity of natural resources in the ground at  $t$  is represented by a line vector  $\mathbf{z}_t$ . The period of production is uniform for all processes. A process  $j$  is defined by quadruplet  $(\mathbf{a}_j, \mathbf{b}_j, \mathbf{c}_j, l_j)$ , with  $\mathbf{a}_j$  the line vector of inputs,  $\mathbf{b}_j$  the line vector of outputs,  $\mathbf{c}_j$  the line vector of natural non-renewable resources (before extraction) used and  $l_j$  the labor coefficient. The wage rate  $\mathbf{w}$  is given in real terms (a line vector of given commodities). Assuming that there is perfect competition, the rate of profit  $r$  is uniform for all processes. Then Kurz and Salvadori write down their system of equations, with  $\mathbf{y}_t$  the column vector of royalties on natural resources and  $\gamma \mathbf{d}$  the share of the surplus going to profit and royalties (given in proportion to a constant column vector of commodities  $\mathbf{d}$ ):

“for each time  $t \in \mathbb{N}_0$ , the following [...] equations are to be satisfied:

$$\mathbf{x}_{t+1} \mathbf{B} \mathbf{p}_{t+1} = \mathbf{x}_{t+1} [(1 + r_t) (\mathbf{A} \mathbf{p}_t + \mathbf{C} \mathbf{y}_t) + \mathbf{l} \mathbf{w} \mathbf{p}_{t+1}] \quad (1.17)$$

$$\mathbf{B} \mathbf{p}_{t+1} \leq (1 + r_t) (\mathbf{A} \mathbf{p}_t + \mathbf{C} \mathbf{y}_t) + \mathbf{l} \mathbf{w} \mathbf{p}_{t+1} \quad (1.18)$$

$$\mathbf{z}_{t+1} \mathbf{y}_{t+1} = (1 + r_t) \mathbf{z}_{t+1} \mathbf{y}_t \quad (1.19)$$

$$\mathbf{y}_{t+1} \leq (1 + r_t) \mathbf{y}_t \quad (1.20)$$

$$\mathbf{x}_t (\mathbf{B} - \mathbf{l} \mathbf{w}) \mathbf{p}_t = (\mathbf{x}_{t+1} \mathbf{A} + \gamma \mathbf{d}) \mathbf{p}_t \quad (1.21)$$

$$\mathbf{x}_t (\mathbf{B} - \mathbf{l} \mathbf{w}) \geq \mathbf{x}_{t+1} \mathbf{A} + \gamma \mathbf{d} \quad (1.22)$$

$$\mathbf{z}_t \mathbf{y}_t = (\mathbf{x}_{t+1} \mathbf{C} + \mathbf{z}_{t+1}) \mathbf{y}_t \quad (1.23)$$

$$\mathbf{z}_t \geq \mathbf{x}_{t+1} \mathbf{C} + \mathbf{z}_{t+1} \quad (1.24)$$

$$\gamma > 0, \mathbf{p}_t \geq \mathbf{0}, \mathbf{y}_t \geq \mathbf{0}, \mathbf{z}_t \geq \mathbf{0}, \mathbf{x}_{t+1} \geq \mathbf{0} \quad (1.25)$$

” (Kurz and Salvadori, 2000).

Eq. 1.17 means that there is production only if the equilibrium rate of profit is obtained. Eq. 1.18 means that it is not possible to obtain more than the equilibrium rate of profit by producing a commodity. Extracting a natural resource is here seen as producing a commodity, so extraction costs are possible, and there is extraction only if the equilibrium rate of profit is earned from this activity.

Eq. 1.19 means that there is storage of natural resources only if the equilibrium rate of profit is earned from it. Eq. 1.20 means that it is not possible to earn more than the equilibrium rate of profit by storing natural resources. Eq. 1.21 and Eq. 1.22 mean that if a commodity is produced without being used in production or consumed in the next period, its price falls to zero. Eq. 1.23 and 1.24 mean that if a natural resource is stored without being used in production or stored again in the next period, its royalty falls to zero.

Furthermore Kurz and Salvadori assume *given amounts of commodities* and exhaustible resources available at time 0. So they are building a neo-Classical system of linear programming, with an optimization program in order to choose the most efficient technological pathway (we can find a similar model in Pasinetti, 1975, Appendix to chapter 6). Then here we are not talking about Sraffian production price, but about allocated price, because initial resources are given and thus prices reflect the efficient allocation of scarce goods.

Given the initial set of natural resources and commodities, their problem is to choose the technology so that they obtain a uniform rate of profit and zero price for excess supply. But in the context of Sraffa, if an input becomes less available, the problem that arises is not a question of technological change but a question of change in the required production levels. Characteristics of both systems are really different. In Kurz and Salvadori model, prices and royalty depends on the allocation of a given set of resources and can be seen as a kind of scarcity index (price is equal to zero if there is overproduction and royalty is equal to zero if there is overconservation). Whereas in Sraffa, prices depend only on the production level and on the distribution of the surplus (between wage and profit) at the given period and there can be a strictly positive price even if there is overproduction (Pasinetti, 1975, Appendix to chapter 6).

Now from equation Eq. 1.19 and equation Eq. 1.23 we get:

$$\mathbf{z}_{t+1}\mathbf{y}_{t+1} = (1 + r_t) (\mathbf{z}_t - \mathbf{x}_{t+1}\mathbf{C}) \mathbf{y}_t \quad (1.26)$$

Then we can add equation Eq. 1.19 and equation Eq. 1.26, and we get, through simplifications:

$$\mathbf{x}_{t+1}\mathbf{B}\mathbf{p}_{t+1} + \mathbf{z}_{t+1}\mathbf{y}_{t+1} = (1 + r_t) (\mathbf{x}_{t+1}\mathbf{A}\mathbf{p}_t + \mathbf{z}_t\mathbf{y}_t) + \mathbf{x}_{t+1}\mathbf{l}\mathbf{w}\mathbf{p}_{t+1} \quad (1.27)$$

Now from equations Eq. 1.17 and Eq. 1.21 we get:

$$\mathbf{x}_{t+1}\mathbf{A}\mathbf{p}_t = \mathbf{x}_t (\mathbf{B} - \mathbf{l}\mathbf{w}) \mathbf{p}_t - \gamma\mathbf{d}\mathbf{p}_t \quad (1.28)$$

Then we can add equations Eq. 1.27 and Eq. 1.28, and we get:

$$\mathbf{x}_{t+1}\mathbf{B}\mathbf{p}_{t+1} + \mathbf{z}_{t+1}\mathbf{y}_{t+1} = (1 + r_t) [\mathbf{x}_t (\mathbf{B} - \mathbf{l}\mathbf{w}) \mathbf{p}_t - \gamma\mathbf{d}\mathbf{p}_t + \mathbf{z}_t\mathbf{y}_t] + \mathbf{x}_{t+1}\mathbf{l}\mathbf{w}\mathbf{p}_{t+1} \quad (1.29)$$

This equation, i.e., Eq. 1.29, shows the relation between the value of inputs and the value of outputs of the system. This relation is close to the one

suggested by Schefold (2001), itself a generalization of Bidard and Erreygers proposition (Bidard and Erreygers, 2001a). With only one natural resource entering into the production of only one commodity  $i$ , Eq. 1.29 is written in Schefold's system as:

$$p_{i,t} + z_{t+1}y_{t+1} = (1 + r)[\mathbf{a}_i\mathbf{p}_t + z_t y_t] + w_t l_i \quad (1.30)$$

But while in Kurz and Salvadori model the value of the rent depends on initial endowments, in Schefold model the value of the rent depends on a back-stop technology (the technology which can replace the technology using the exhaustible resource) and the expected life of the mine. The rent is calculated at the period of exhaustion, then backward until the initial period through the assumption of Hotelling's rule. However, in some sense, both the models are back-stop technology models: in the first one the existence of a backstop technology is just a hypothesis in order to save the economy from destruction whereas in the second model, a backstop technology is mandatory in order to solve the system.

But the fact that a future technology is needed to solve the value problem in the present period is clearly in contradiction with the way Sraffa constructed his model, prices being entirely dependent on present technology and present distribution. Parrinello (2004) says that in Kurz and Salvadori and Schefold models, "the determination of equilibrium prices is not self-contained in each period because of special intertemporal link". In Kurz and Salvadori, value is related to the initial endowments (that is why we can talk about allocated prices, and not about prices of production) and in Schefold, value is related to the future back-stop technology (a change in this technology causes a change in the value of the royalty in the present).

So we can see that:

1. Kurz and Salvadori, as well as Schefold and Bidard and Erreygers, start from the fact that royalties exist, but they do not explain why it is so, and their models do not show it either.
2. Then they say that it is possible to earn a rate of profit from the natural resource storage activity, because otherwise owners of such capital should sell everything at the first period.
3. Then equilibrium assumption ensures that the rate of profit that is earned by storing natural resources is the equilibrium one. Thus the Hotelling's rule is deduced from this assumption (albeit from two different methods).
4. Finally this has an impact on relative prices, especially if one natural resource is a basic (see subsection 1.3.7).

I will explain in the next subsection why the first three points (existence of royalties, profit on conservation industry and equilibrium assumption) cannot cope with the Sraffian framework.

### 1.3.4 Is introducing Hotelling's rule a change in the Sraffian direction?

#### 1.3.4.1 Theory of value

The reasons why the Hotelling's rule cannot be applied in a Sraffian framework lies in the notion of 'royalty' in Hotelling and the way Sraffa defines value. In Hotelling, royalty comes from the fact that natural resource (not yet extracted) is seen as capital.<sup>20</sup> But why it is seen as capital? It is so because in the future it may be possible to earn something by extracting the natural resource. Value comes from expectations - a subjective consideration.

Furthermore royalty is sometimes renamed as the "cost of use" of the exhaustible resource, or "the user cost".<sup>21</sup> It means that we are giving up future profits by using the resource now; the royalty is rewarding owners of the natural resource for future consumer's satisfaction, otherwise everybody would extract everything now. But Sraffa's prices reflect only past and present exchanges, not future ones.

Actually the work of Sraffa goes as this (I follow here the new interpretation of Sinha, 2012):

1. It is a description of the real market at one moment of time;
2. The only magnitudes taken into account are objective magnitudes: physical quantities of commodity inputs and employed human labor used and physical quantities of outputs;
3. Then the system of value can move with one degree of freedom: this is closed when the wage (or the rate of profit) is fixed in an exogenous way.

Thus there is no room for expectation from the agents: no subjective data are taken into account. So the essential theory of value behind the Hotelling's rule does not fit with Sraffa's theory.

#### 1.3.4.2 The conservation industry

Furthermore royalties in Hotelling can be seen as the profit of the conservation industry (Kurz and Salvadori, 1997). This is a strange industry: there is no worker, and no need for inputs from other industries. Apparently there is no creation of value by keeping a resource in the ground, but in the Hotelling theory, owner of a stock of exhaustible resources should earn royalties on conservation.

<sup>20</sup>"How much of the proceeds of a mine should be reckoned as income, and how much as return of capital?" (Hotelling, 1931, p. 139).

<sup>21</sup>"The exhaustible resource is commodity  $n$  [...] Its value in use is the same as that of its future substitute in that both render the same services to all users of the commodity" (Scheffold, 2001). "The cost of production of the commodity is equal to its cost of extraction plus a user cost (due to the prospective exhaustion of the ore in the ground)" (Scheffold, 2001).

This is not in accordance with Sraffa's value theory. Pasinetti shows that it is possible to reduce "prices of every commodities into a sum of profit weighted quantities of labour" (Pasinetti, 1973), even in case of joint production. But this reduction is not possible anymore if an industry is not using labor. The implication of this is that political economy, from the point of view of Marx and Sraffa, should be abandoned. In their approaches, the economic value comes from socially approved labor: by giving value to a resource kept in the ground without labor, we are changing the theory of value. Now every good can be a source of economic value as long as it can be a source of user value: and then every owner of such goods could ask for a reward on his conservation industry. If we allow the Hotelling's rule, then we allow the neoclassical theory of value starting from Menger, Jevons and Walras, and the distribution theory behind it.

### 1.3.4.3 The result of equilibrium due to perfect competition

Finally, for Hotelling and his followers, perfect competition gives us a uniform market rate of interest and this allows us to adequately discount future profits and to find the Hotelling's rule. But for Sraffa there is no equilibrium a priori.<sup>22</sup> This is best illustrated by this draft 'Preface' of Sraffa's book, *Production of Commodities by Means of Commodities*:

"This is not proposed as a complete system of equilibrium. The data assumed are not sufficient to determine either distribution or values. Only the effects of hypothetical, arbitrarily assumed extra data (such as wages, or the rate of profits) are discussed. . . . It is offered as a preliminary and there is no a priori reason why, on the basis of it, an equilibrium system should be built: there is some room left for it, as this is confessedly indeterminate; but the question is whether there is room enough for the marginal system."  
(D3/12/46:20, dated 2 April 1957; quoted in Sinha, 2013)

So in a Sraffian framework prices should not be inferred from subjective appreciation, but only from observable data (quantities exchanged). Sraffa was so determined in this direction that he was even reluctant to use the amortisation technique on fixed capital (Kurz and Salvadori, 2005). But the Hotelling's rule  $\mathbf{y}_{t+1} = (1 + r)\mathbf{y}_t$  is not an observable data. This rule may be inferred from observable data: this is precisely what Parrinello (2004) tries to do, incorporating royalty as an intensive rent, and then showing that a given technological path could allow the rent to evolve in a way consistent with the Hotelling's rule. But the Hotelling's rule cannot be given in the premises without breaking Sraffa's position on the theory of value.

<sup>22</sup>The main argument for the theory of equilibrium in Sraffa's work is that he was reasoning with a uniform rate of profit. But actually this uniform rate of profit in Sraffa's equations is not the result of a gravitation process but the inevitable result of the system of equations. It is not an equilibrium rate of profit, but rather an ex-post accounting rate of profit of the real economy under study during one period of production (Sinha, 2012).

### 1.3.5 What could be a Sraffian proposition on exhaustible natural resources

I will argue here that Sraffa's system, without introducing any subjective notion and assumption on equilibrium, is able to explain the exhaustible resource problem.

#### 1.3.5.1 The question of constant return to scale

One criticism against this system is about the use of constant returns to scale (e.g. see Solow, 2014). In this regard, an easy criticism was put forward by Menger (1871): if constant returns to scale is assumed then given an exhaustible natural resource of uniform quality and uniform location, the resource price after extraction will stay the same even if it becomes exhausted. But Sraffa's model should not be confused with Leontief one, or with the theory of Ricardo: Sraffa warned explicitly that no assumption regarding constant returns to scale is made in his work (see Sraffa, 1960, p. v).

Should we assume constant returns to scale in the case of extraction of exhaustible resources?<sup>23</sup> Firstly, constant returns are extremely rare, if not non-existent, in the case of natural resource extraction. The general law is that the more a resource becomes scarce, the more difficult is its extraction (this concerns all extractive industries, but also forestry, fishery, etc.).<sup>24</sup>

Secondly, here is what happens when the natural resource becomes scarce: either demand stays at the same level or the demand decreases (the commodity is substituted with another good). If the demand stays up, either a new technique of production will be introduced in order to satisfy the demand, giving rise to a rent on the more profitable technique, or the system will break down. So Menger's criticism is not valid because, for any given exhaustible resource, it is really unlikely that we observe constant returns to scale for its extraction and, at the same time, that no second technique for the extraction would appear to answer the demand.

Below I present a model of an exhaustible resource, say coal. A commodity is produced, so a natural resource becomes a commodity only after extraction: in our case I make the distinction between the natural resource conserved in the ground "Coal", which bears no price, and the commodity "Extracted Coal".

#### 1.3.5.2 Two processes, constant returns to scale

Let us first have one mine of Coal, privately owned. Let us say that Extracted Coal is a basic commodity, entering in the production of its own process of production as well as in the process of production of wheat; and let us first assume that there are constant returns to scale operating in both industries. Table 1.2 shows the system of production.

<sup>23</sup>The assumption of zero cost of extraction is just one example of the assumption of constant returns to scale in this case.

<sup>24</sup>One exception could be the case where all lands are cultivated and some disappear because of urban expansion.



Table 1.2: system of production of wheat and Extracted Coal, constant returns to scale.

Input			Outputs	
Wheat	Extracted Coal	Labor	Wheat	Extracted Coal
$a_{11}$	$a_{12}$	$l_1$	$b_{11}$	0
$a_{21}$	$a_{22}$	$l_2$	0	$b_{22}$

The productivity of the extraction of Coal depends on the initial amount of Coal in the mine,  $C(0)$ . It is assumed that we have the extraction function Eq. 1.31:

$$b_{22} = \alpha C(0) \quad (1.31)$$

With  $\alpha$  a constant and  $0 < \alpha < 1$ .

Then prices of production are:

$$b_{11}p_1 = (1+r)(a_{11}p_1 + a_{12}p_2) + l_1w \quad (1.32)$$

$$\alpha C(0)p_2 = (1+r)(a_{21}p_1 + a_{22}p_2) + l_2w \quad (1.33)$$

With  $r$  the uniform rate of profit (as it must be uniform in Sraffa's equations, and not because of an equilibrium assumption, Sinha, 2012), and  $w$  the wage. Then we have an expression of the price of extracted coal which is independent both of time and, more importantly, of the quantity of resource left:

$$p_1 = \frac{(1+r)a_{12}p_2 + l_1w}{b_{11} - (1+r)a_{11}} \quad (1.34)$$

$$p_2 = \left[ \frac{(1+r)a_{21}l_1w}{b_{11} - (1+r)a_{11}} + l_2w \right] / \left[ \alpha C(0) - (1+r)a_{22} - \frac{(1+r)^2 a_{12}a_{21}}{b_{11} - (1+r)a_{11}} \right] \quad (1.35)$$

Here we cannot have any information about the fact that the natural resource is scarce or not: but as I said earlier, this model is highly implausible. In real systems, cost of extraction should be correlated with the quantity of the natural resource left. And as Sraffa stresses, the indication of scarcity of the natural resource can be reflected in the presence of two processes producing one commodity while at least one process is using the natural resource as an input. Let us introduce these two important modifications, first separately and then together.

**1.3.5.3 Two processes, non constant returns to scale**

First if we want to have a more realistic function of extraction, it should at least be in the form:<sup>25</sup>

$$b_{22}(t) = \alpha C(t) \quad (1.36)$$

That is, the extraction cost is positively related with the stock of coal left in the ground.

The price of extracted coal is then time-dependent:

$$p_2(t) = \left[ \frac{(1+r)a_{21}l_1w}{b_{11} - (1+r)a_{11}} + l_2w \right] / \left[ \alpha C(t) - (1+r)a_{22} - \frac{(1+r)^2 a_{12}a_{21}}{b_{11} - (1+r)a_{11}} \right] \quad (1.37)$$

And if the shares of the surplus going to wages and to profits do not change, the price of coal increases as the quantity of coal left in the ground  $C(t)$  decreases.

**1.3.5.4 Three processes, constant returns to scale**

Secondly, let us go back to the first case where the extraction function is represented by Eq. 1.31. If the extraction of coal cannot satisfy the demand, it allows for a new technique to come into play, e.g. production of Synthetic Coal, as in table 1.3:

Table 1.3: system of production of wheat, Extracted Coal and Synthetic Coal, with constant returns to scale.

Inputs			Outputs	
Wheat	Coal	Labor	Wheat	Coal
$a_{11}$	$a_{12}$	$l_1$	$b_{11}$	0
$a_{21}$	$a_{22}$	$l_2$	0	$b_{22}$
$a_{31}$	$a_{32}$	$l_3$	0	$b_{32}$

Now, as Synthetic Coal and Extracted Coal have the same price, in order to solve the price system a rent has to be integrated. There are various ways to do it, depending if the new technique is more profitable (technological improvement), less profitable (expression of a real scarcity) or if the rent is captured by the owner of the mine or by the workers. We will assume that the new technique is less profitable and that rent  $\rho$  goes in the pocket of the mine owner:

$$b_{11}p_1 = (1+r)(a_{11}p_1 + a_{12}p_2) + l_1w \quad (1.38)$$

<sup>25</sup>This idea comes from the economics of renewable resources (Gordon, 1954; Schaeffer, 1954), following a presentation from Erreygers (2014) on this subject.

$$\alpha C(0) p_2 = (1+r)(a_{21}p_1 + a_{22}p_2) + l_2w + \rho \quad (1.39)$$

$$b_{32}p_2 = (1+r)(a_{31}p_1 + a_{32}p_2) + l_3w \quad (1.40)$$

The price of the Extracted Coal/Synthetic Coal and the rent are then:

$$p_2 = \left[ \frac{(1+r)a_{31}l_1w}{b_{11} - (1+r)a_{11}} + l_3w \right] / \left[ b_{32} - (1+r)a_{32} - \frac{(1+r)^2 a_{12}a_{31}}{b_{11} - (1+r)a_{11}} \right] \quad (1.41)$$

$$\rho = \left[ \alpha C(0) - (1+r)a_{22} - \frac{(1+r)^2 a_{12}a_{21}}{b_{11} - (1+r)a_{11}} \right] p_2 - \left[ \frac{(1+r)a_{21}l_1}{b_{11} - (1+r)a_{11}} + l_2 \right] w \quad (1.42)$$

This rent again is not time-dependent.

### 1.3.5.5 Three processes, non constant returns to scale

But now if we want to add both modifications, when the extraction function is represented by Eq. 1.36, the system of price becomes:

$$b_{11}p_1(t) = (1+r)[a_{11}p_1(t) + a_{12}p_2(t)] + l_1w \quad (1.43)$$

$$\alpha C(t) p_2(t) = (1+r)[a_{21}p_1(t) + a_{22}p_2(t)] + l_2w + \rho(t) \quad (1.44)$$

$$b_{32}p_2(t) = (1+r)[a_{31}p_1(t) + a_{32}p_2(t)] + l_3w \quad (1.45)$$

And then price of the Extracted Coal/Synthetic Coal and rent become:

$$p_2 = \left[ \frac{(1+r)a_{31}l_1w}{b_{11} - (1+r)a_{11}} + l_3w \right] / \left[ b_{32} - (1+r)a_{32} - \frac{(1+r)^2 a_{12}a_{31}}{b_{11} - (1+r)a_{11}} \right] \quad (1.46)$$

$$\rho(t) = \left[ \alpha C(t) - (1+r)a_{22} - \frac{(1+r)^2 a_{12}a_{21}}{b_{11} - (1+r)a_{11}} \right] p_2 - \left[ \frac{(1+r)a_{21}l_1}{b_{11} - (1+r)a_{11}} + l_2 \right] w \quad (1.47)$$

Now an interesting feature of it is that the price of Extracted Coal and Synthetic Coal is not time-dependent, as its price depends on the third technique (the least profitable one - Synthetic Coal production). Thus only the rent is time-dependent, and the rent decreases as the extraction cost increases. If the extraction cost gets too high, the Synthetic Coal process could become more profitable than extracting coal from the ground: at that point, the rent will become negative, meaning that it will be earned by the owner of the Synthetic Coal process.

### 1.3.6 Concluding comments

The price of the Coal mine could depend on the rent that the buyer expects to get (using the rate of profit as a depreciation rate for future profit). The current rent and profit rate can be calculated by Sraffa's method. In case of an arbitrage between two competitive investments, a calculation of the value of the Coal mine could be:

$$p_{mine} = \int_0^{\infty} [r(t) \alpha C(t) p_2(t) + \rho(t)] x_2(t) e^{-r(t)t} dt \quad (1.48)$$

With  $x_2(t)$  is the intensity of the extraction process. And from that one could argue that the value of Coal in the ground is  $v_{Coal} = p_{mine}/C(t)$ . But this calculation cannot be done without some expectations on future rate of profit, future demand and future prices. On that subject Sraffa cannot help, so the price of the mine, as well as price of Coal as a natural resource not extracted yet (or price of a land not cultivated yet) should stay indeterminate within the bare Sraffian framework.

A convention about what future rates should be applied may be conventionally given. These rates don't have to be the same as the rates that actualize in the future; for example, 20 years of current prevailing rent used to be the convention to determine the price of land at the present. Then, starting from this convention, price of natural resource into the ground can be found. But then we have a conventional price and it should be pointed out that it does not reflect the true value of the resource, neither its "cost of use".

We found here again the difference between the value theory of the Austrian school and of Hotelling and the value theory of Sraffa. For the first ones, if one land is used in one process of production, thus, not only this land, but all land have a value, defined by the consumer's satisfaction that we can create with this land (now and in the future – that is why even a not yet used land can receive a royalty). Hotelling was in the same line of thought when he is assuming a royalty on conservation process. But for Sraffa, value derives only from production, and land not used in production cannot receive a rent.

The analysis in subsection 1.3.5 can easily be widened to other natural resources: land of course, but also renewable resources. There is still lot of work to be done in order to understand the relationships between rents and biophysical limitations of natural resource extractions.

### 1.3.7 Appendix

Here I prove that there is a change in relative prices when the Hotelling's rule is introduced in a Sraffian framework, starting from Kurz and Salvadori's model, described in subsection 1.3.3.

Let us suppose that wages are set to zero (thus the rate of profit  $r_t$  becomes the maximum rate of profit  $R_t$ ). As coefficients of production are constant, we

can clearly see that the price system is changing when we add the Hotelling's rule. If there was no Hotelling's rule then Eq. 1.27 would be written as:

$$\mathbf{x}_{t+1}\mathbf{B}\mathbf{p}_{t+1} = (1 + R_t)\mathbf{x}_{t+1}\mathbf{A}\mathbf{p}_t \quad (1.49)$$

The scarcity of the natural resource is not anymore taken into account: if the resource gets scarcer the activity level will be lower for those processes using (directly or indirectly) the natural resource. But as there are constant returns to scale, the price relation would not change. As the technology is not changing, the maximum rate of profit has no reason to change from time to time, so we can change the system into:

$$\mathbf{x}_{t+1}\mathbf{B}\mathbf{p}_{t+1} = (1 + R)\mathbf{x}_{t+1}\mathbf{A}\mathbf{p}_t \quad (1.50)$$

This maximum rate of profit  $R$  is the standard rate of profit. Assuming the Hotelling's rule, royalties increase from period to period and then prices may change from period to period. However, is it possible that introducing royalties does not change the standard system, and thus does not change relative prices and  $R$ ? From equation Eq. 1.27 we should get:

$$\mathbf{x}_{t+1}\mathbf{B}\mathbf{p}_{t+1} = (1 + R)(\mathbf{x}_{t+1}\mathbf{A}\mathbf{p}_t + \mathbf{z}_t\mathbf{y}_t) - \mathbf{z}_{t+1}\mathbf{y}_{t+1} \quad (1.51)$$

If introducing royalties does not change relative prices, we should have an equality between relations Eq. 1.50 and Eq. 1.51:

$$(1 + R)\mathbf{x}_{t+1}\mathbf{A}\mathbf{p}_t = (1 + R)(\mathbf{x}_{t+1}\mathbf{A}\mathbf{p}_t + \mathbf{z}_t\mathbf{y}_t) - \mathbf{z}_{t+1}\mathbf{y}_{t+1} \quad (1.52)$$

Simplifying we get:

$$(1 + R)\mathbf{z}_t\mathbf{y}_t = \mathbf{z}_{t+1}\mathbf{y}_{t+1} \quad (1.53)$$

And from equation Eq. 1.19 we have:

$$(1 + R)\mathbf{z}_t\mathbf{y}_t = \mathbf{z}_{t+1}\mathbf{y}_t \quad (1.54)$$

So in order that prices do not change with the introduction of royalties, it has to be that  $z_t = z_{t+1}$ ; i.e., that there should be no decrease in the stock or in other words, exhaustible natural resources should actually not be used. So we can conclude that royalties do not influence the system of price only if natural resources are not basic goods.

## 1.4 Waste, pollution, and renewable resources

On the contributions that tackle some environmental problems apart from the case of exhaustible resources, some try to assess the waste treatment problem and how to take into account recycling in a Sraffian framework (Lager, 2001; Hosoda, 2001; Kurz, 2006); others to take into account the pollution of a natural resource and to implement a polluter-pay principle in a Sraffian model (Quadrio Curzio and Pellizzari, 2003); and others to describe the management of renewable resources, when their extraction could lead to their extinction (salmon model in Kurz and Salvadori, 1995, p. 351-357, fish farming vs. fish in the wild in Erreygers, 2014).

### 1.4.1 Waste management and recycling

#### 1.4.1.1 Lager

Lager (2001) deals with the following joint production problem: if two commodities are jointly produced by two different processes, it is possible that their production exceeds the requirement for use (or the effective demand if they are only consumption goods). Then what would be their prices? Is there free disposal? I think the solution is to say that they must dispose the surplus, so that they buy a service for disposal.

For Lager the solution is to add a third process using the commodity in excess production (for instance product 1) to produce the second commodity (for instance product 2). He says that this process could be viewed as “a costly disposal process which absorbs some quantities of the unwanted product 1 and produces some quantities of product 2 by means of labour”. Thus product 1 will have a negative price: “the producers of bads have to pay for delivery and the users of the bad obtain revenues for taking the unwanted product, i.e. the price of the bad is negative”.<sup>26</sup> Lager also makes reference to physical laws of nature, such as “the principle of conservation of mass-energy” to explain why the rule of free goods, or of free disposal, should be discarded.<sup>27</sup>

Then he develops a model where there are three possibilities for a waste producer:

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<sup>26</sup>I am reluctant to adopt this idea of a negative price, as I think that a price is given to commodity as soon as it is exchanged on the market. If the waste is disposed by the industry who produces this waste, a cost can be attached to it: some inputs will have to be bought on the market in order to successfully dispose it, but there is no exchange of the waste on the market, and thus no price. If the waste is given to an other industry which will dispose it, the other industry is selling the disposal service, and a positive price is attached to this service, related to the costs of this industry: again, no price should appear on the waste. See subsection 1.4.1.3 for mathematical representation of this point.

<sup>27</sup>The laws of nature such as thermodynamic laws indeed represents strong constraints for the economic process, and these constraints must be taken into account if one is interested in the dynamics of a system of production; but it is important to notice that in order to calculate static Sraffian prices, there is no need to consider them. As Sraffa's system is an economic one looking at commodities (goods and services) exchanged in a market, there is no need to consider what is not exchanged in the market for the price calculation.

“someone who produces potential bads has several options: (i) he may find somebody who takes the product, (ii) he may buy costly permits and use the right to dispose of excess production, or, if that is technically feasible, he may (iii) use an alternative method which is more expensive but by which excess production can be avoided or, at least, reduced” (Lager, 2001).

If the disposal does not exceed tolerated levels for environmental protection, permits of disposal are free. Otherwise, the law of supply and demand set a positive price for permits. The free competition is also assumed in the market (whereas in the new interpretation - or in the work of Pasinetti - it is not necessarily the case), and he develops a cost-minimizing system with land and renewable resources, which is in the same spirit as the one developed by Kurz and Salvadori (2000).

#### 1.4.1.2 Hosoda

Hosoda (2001) thinks that Sraffian economics are static long-run equilibrium economics and that prices gravitates around long-term equilibrium prices. But for him “dynamic factors are also important”, and that why he is interested into exhaustible resources and waste management.

He develops a model in the spirit of the corn-guano model developed by Bidard and Erreygers (2001a) where waste, produced by process 1, must be disposed in a landfill (process 2) or recycled (process 3). Landfill is considered as an exhaustible resource, so at one moment in time recycling will be the only option left - recycling is the back-stop technology. As recycling is assumed less productive than landfilling, recycling is not activated until landfilling is not possible anymore. Hosoda adds that “residuals must have a negative price”.<sup>28</sup>

Process 1 at the beginning buys the service of landfilling. Then, as landfill is exhausted, the price of landfilling increases: here Hosoda makes reference to the Hotelling rule to justify this increase.<sup>29</sup> At the end of the landfill, the recycling process becomes equally profitable and will replace landfilling.

#### 1.4.1.3 Kurz

Kurz (2006) acknowledges that the economic system is constraint by the availability of natural resources and by the physical laws governing transformations and exchanges; furthermore, following Jevons (1871), he notices that joint production is a widespread phenomena: “multiple-products processes are ubiquitous, and joint production is the rule” (Kurz, 2006). With joint-production, processes not only produces goods, defined as “products capable of satisfying human needs and wants”, but also bads, defined as “products nobody wants and which may even be harmful to humans if not disposed of safely by means

<sup>28</sup>See subsection 1.4.1.3 for a development of my position on this point.

<sup>29</sup>See section 1.3.1 for a critique of such use in the Sraffian framework. I think it is possible to come up with the same result by discarding the Hotelling rule and by assuming instead non constant returns to scale on the landfill process.

of disposal processes”. Negative prices are attached to bads: “while with goods, money and product move in opposite direction, with bads, the direction is the same” (Kurz, 2006).

Besides, the distinction between goods and bads can not be known in advance: one as to look at the conditions of production and at the exchanges on the market to have the answer. But in order to calculate the price of a joint-production system, one has to ensure that there are the same number of processes and of resources used/or produced.<sup>30</sup>

Then Kurz develops a simple model with costly disposal. Starting from one process producing one good and one waste, he first introduces costly disposal by the addition of one process using the waste as inputs but producing nothing:

$$\begin{array}{rcccccc}
 & \textit{Labor} & \textit{Good} & \textit{Waste} & & \textit{Good} & \textit{Waste} \\
 \textit{Method 1} & l_1 & a_{11} & 0 & \rightarrow & b_{11} & b_{12} \\
 \textit{Method 2} & l_2 & a_{21} & b_{12} & \rightarrow & 0 & 0
 \end{array} \tag{1.55}$$

So method 2 is the technology which is able to dispose the waste. Kurz first states that this technology is used by an different industry than the one using method 1. The system of value can thus be represented in this way:

$$\begin{aligned}
 (1 + \pi) a_{11} p_g + l_1 w &= b_{11} p_g + b_{12} p_w \\
 (1 + \pi) (a_{21} p_g + b_{12} p_w) + l_2 w &= 0
 \end{aligned} \tag{1.56}$$

With  $p_g$  the price of the good and  $p_w$  the price of the waste,  $\pi$  the profit rate and  $w$  the wage. Here the price of the waste must be negative:

$$b_{12} p_w = -a_{21} p_g - \frac{l_2 w}{(1 + \pi)} \tag{1.57}$$

Then Kurz states that system 1.56 is equivalent to the following system:

$$(1 + \pi) (a_{11} p_g + a_{21} p_g) + (l_1 + l_2) w = b_{11} p_g \tag{1.58}$$

In this new system, the disposal of the waste is done by the same industry which produces it, and the waste does not appear anymore in the value system. But actually, if both systems are equivalent on the physical level, they are not on the value level: as soon as the rate of profit is different from zero, the value of the output is different. Indeed, in system 1.56, the value of the output is:

$$((1 + \pi) a_{11} + a_{21}) p_g + \left( l_1 + \frac{l_2}{(1 + \pi)} \right) w = b_{11} p_g \tag{1.59}$$

Then which representation is the good one? They actually represent both situations that could happen in the market: waste processing could be outsourced or handled internally. Nevertheless, for me, the first representation

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<sup>30</sup>Mill, for instance, discarded the classical theory of price precisely because in the case a system consisted of a single process, with joint production, it is not possible to assert the prices. But if we assume that it is always possible to represent the system as a square one, i.e. as “a set of industries ... equal in number ... to the different things that are produced and/or used as means of production” (Sraffa, 1960, § 90), then prices can be calculated.



(system 1.56) is clearly wrong, as it shows the waste as a product exchanged on the market, whereas it is the service of disposal, with its related cost, which is actually traded. Thus a good representation of a situation where the first industry, who produces the waste, outsources the disposal of its waste, would be:

$$\begin{aligned} (1 + \pi)(a_{11}p_g + b_{12}p_d) + l_1w &= b_{11}p_g \\ (1 + \pi)(a_{21}p_g) + l_2w &= b_{12}p_d \end{aligned} \quad (1.60)$$

Here we can see that outsourcing the disposal process is more costly for the first industry than handling it internally. But of course, if the disposal industry is specialized in this activity and experiences increasing returns to scale, it is to be expected that the price of the disposal service will be cheaper.

### 1.4.2 Pollution and the polluter-pay principle

Quadrio Curzio and Pellizzari (2003)<sup>31</sup> are concerned with the pollution of non-privately owned natural resources. They start with a Sraffian single production model defined by its matrix of technology  $\mathbf{A}$ , with the coefficients concerning the production of one unit of the  $m$  goods produced by the system, and its line vector of labor coefficient,  $\mathbf{l}$ . Then they define a line vector  $\mathbf{r}$ , whose coefficients  $r_i$  expresses the use of a natural resource needed for the economic process  $i$  in order to produce one unit of good  $i$  (single production system). The total use of the natural resource can not exceed quantity  $R$ , which is the total quantity of the resource existing in the environment:

$$m_R = \mathbf{r}\mathbf{y} \leq R \quad (1.61)$$

With  $\mathbf{y}$  the column vector of activity levels for all processes (equal to the vector of produced quantities  $\mathbf{q}$  because only single production is allowed and

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<sup>31</sup>Quadrio Curzio (Quadrio Curzio and Pellizzari, 1999; Quadrio Curzio, 2011), from a Sraffian perspective, and with inspirations from Leontief and Von Neumann, develops a multi-sectoral model where rents and scarce resources are in the center of the analysis.

He first deals with a static model, and looks at the order of efficiency and of profitability of the processes. Then he studies the effect of variations of the distribution and of the activity levels: he thus shows the important role of rent in the distribution, as it changes the relation between wage and profit. He then compares technologies, i.e. a set of techniques (with single or joint production), following several criteria: efficiency, structure, size, depending on the decrease of the resources and the increase of production. He thus defines *technological rent* as the rent which is connected with one particular technology (and not with one particular technique), and *technological scarcity* as the scarcity which exists as soon as constraints from scarce resources appears at the structural level of production. He also defines technological progress as the capacity for an economic system to reduce its constraints on growth.

Finally, Quadrio Curzio studies the order of efficiency of different processes, in a static and dynamic way, and the way the constraints lead to the activation of certain processes and to the reduction of production growth. The evolution of rents can lead to conflicting situations between the different agents when they have to choose the processes to activate, because they have different interests (seeking for the maximal rents or for the maximal profits for instance). This situations may lead to the development of some innovations to the detriment of others.

because matrix is normalized such as the matrix of output is the identity matrix) and with  $m_R$  the quantity of the natural resource used in each period of production by the system.

They assume then the possibility of a recycling, or of a remediation, of the natural resource, in order to partially replenish the natural stock. This replenishment is considered to be non complete, and its cost, in terms of inputs needed for the replenishment process, is attributed to the industries, proportionally with their use of the natural resource, following the polluter-pay principle (OECD, 1972). In order to do so, they define a line vector  $\mathbf{a}_R$  with coefficients  $a_{iR}$  representing the quantity of commodity  $i$  needed for the maximum possible replenishment of one unit of the natural resource. Then each process consuming the natural resource, in addition with the production of their own commodity, will have to produce the commodities needed to replenish the maximum of what they have consumed, i.e. they will have to produce vector  $\mathbf{a}_R$  multiplied by coefficient  $r_i$ .

Thus remediation is treated in the same way as internal waste disposal in Kurz (2006). The only difference is that the quantity of labor  $L_R$  which is needed directly for the replenishment process is not handled by the industries: the replenishment process is operated outside the economic system, and the wage needed for this operation is not accounted when the profitability criteria is used for the choice of technique.

Each process  $\mathbf{a}_i$  must produce commodity  $i$  et the vector  $r_i \mathbf{a}_R$ ; they can be represented in this way, with a prime for transpose vector:

$$\mathbf{a}'_i + r_i \mathbf{a}'_R = [ a_{1i} + a_{1R}r_i \quad a_{2i} + a_{2R}r_i \quad \dots \quad a_{mi} + a_{mR}r_i ] \quad (1.62)$$

And each labor coefficient  $l_i$  becomes:

$$l_i (1 + a_{1R}r_i + a_{2R}r_i + \dots + a_{mR}r_i) \quad (1.63)$$

We can then construct a matrix  $\mathbf{R}$  containing all inputs coefficient for the reconstitution of the natural resource:

$$\mathbf{R} = \begin{bmatrix} a_{1R}r_1 & a_{1R}r_2 & \dots & a_{1R}r_m \\ a_{2R}r_1 & a_{2R}r_2 & & \vdots \\ \vdots & & \ddots & \\ a_{mR}r_1 & \dots & & a_{mR}r_m \end{bmatrix} \quad (1.64)$$

By post-multiplying matrix  $\mathbf{R}$  with the activity vector  $\mathbf{y}$ , we get the column vector  $\mathbf{q}_R$  of the quantities produced in order to replenish the natural resource:

$$\mathbf{R}\mathbf{y} = \mathbf{q}_R \leq \mathbf{q} \quad (1.65)$$

Regarding the choice of techniques, two criteria could be considered: the criteria of maximal productivity (which is the higher uniform rate of surplus  $s$  - if all the surplus is reinvested, this rate is equal to the maximal rate of

growth), and the criteria of maximal profitability (which is the higher rate of profit  $\pi$ ).

About the first criteria, the physical system becomes, when we include matrix  $\mathbf{R}$ :

$$[1 + s][\mathbf{A} + \mathbf{R} - \mathbf{I}]\mathbf{y} = \mathbf{0} \quad (1.66)$$

Hence we can look, for different technologies  $\mathbf{A} + \mathbf{R}$  which are the ones producing the highest uniform rate of surplus. But this criteria is only efficient if the natural resource is entirely replenished: otherwise, a choice has to be made between better replenishment of the natural resource and higher production of surplus. This choice is influenced by subjective considerations on present and future expectations: for instance, the immediate use of the natural resource could be required for the developing countries, but this would lower the possibilities for the future generations to use it, without taking into account the fact the effects of the reduction of the natural resource on the environment and on ecosystems are usually unpredictable.

About the second criteria, one possibility is to set a price on the natural resource, so the choice can be made regarding the reduction of economic as well as environmental costs. This price  $p_R$  could then be divided into two components: one part covers the economic cost of replenishment<sup>32</sup> and the other part is an estimation of the cost of the loss of the part of the natural resource which can not be reconstituted, represented by the environmental rent  $\rho$ :

$$p_R = [1 + \pi]\mathbf{p}\mathbf{a}_R + w\mathbf{l}\mathbf{a}_R + \rho \quad (1.67)$$

With  $\mathbf{p}$  the line vectors of price. The price system is then represented as follows:

$$[1 + \pi]\mathbf{p}[\mathbf{A} + \mathbf{R}] + w[\mathbf{l} + \mathbf{l}\mathbf{R}] + \rho\mathbf{r} = \mathbf{p} \quad (1.68)$$

The system is undetermined, because there are  $m + 3$  unknowns and  $m$  equations. Even if one distribution variable is given and a numeraire is chose, there one degree of liberty left. Thus the efficiency of the profitability criteria depends on the relevance of the value attributed the the environmental rent<sup>33</sup>.

<sup>32</sup>But, again, the cost of labor  $L_R$  needed for the replenishment process is not taken into account.

<sup>33</sup>Environmental economics tries to develop economic methods in order to properly assess the level of this rent (Pearce and Turner, 1990; Barde and Pearce, 1991; Faucheux and Noël, 1995). This methods belongs to three different approaches:

1. The usual market approach analyzes transactions on the market and tries to connect market prices with the environmental distinctive features. The function of production method considers the environment as one of the factors of production and looks at the influence of changes in the quality of natural resources on prices; the dose-response method establishes a relation between pollution and the rate of disease and can then establish the costs related to an increase in pollution; the evaluation of defensive expenditures looks at the costs generated by the mitigation or the adaptation to environmental change.
2. The implicit market approach tries to estimate preferences and expenditures related to

This leads Quadrio Curzio and Pellizzari to conclude on the impossibility to find a unique criteria for the choice of techniques as soon as one non privately owned natural resource is taken into consideration in the model: a political choice is needed.

### 1.4.3 Renewable resources

There are very few Sraffian works on renewable resources: interestingly, Gibson (1984) suggests that the treatment between non-renewable and renewable resources should not be different in a Sraffian framework. He is first looking at one natural exhaustible resource as divided in numerous stocks. The cost of exploration in order to find a new stock (e.g. a new mine) can be high in case of scarce natural resources. This cost should be payed off, little by little, through the life expectancy of the stock (he refers to the process of amortisation after the construction of a fixed capital, e.g. a machine or a building, Sraffa, 1960, chapter X). If the stock has a very long life expectancy, or even an infinite life (i.e. if the natural resource is renewable), then the cost of exploration is payed off during an arbitrary period of time. There is no price on the natural resource and no Hotelling rule. Gibson's analysis is close to the Ricardian analysis on mines as a renewable natural resource given that the cost of the exploration is more or less constant (see Kurz and Salvadori, 2009 for a detailed analysis of the Ricardian methodology).

Kurz and Salvadori (1995, p. 351-357) build the Salmon model, where Salmon is a renewable resource and a non-basic commodity. They demonstrate, starting from usual assumptions about the dynamics of the stock of renewable resources, that it is possible to have a stable extraction of the resource (no change of the stock between periods), but also that the resource can be depleted. They interpret the stable position as a long-term equilibrium.

Erreygers (2014) transforms their model into a Corn-Tuna model: I will focus here on the Erreygers' work. He studies fish production, looking at two different processes producing tuna, fishing on sea (Wild Tuna Method) or aquaculture (Farmed Tuna Method). For the first process, the stock of tuna in the sea depends on fishery and on population dynamics:

“in the absence of fishing, the population  $P$  tends to grow according to its natural increase  $n$ , which can be seen as a function

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these preferences by looking at the behaviors in relation with environmental resources. The hedonic pricing method looks at the influence of the environment on transactions that are more or less concerned with environmental criteria, for instance the level of house rents or the wages of people willing to work in the area. The travel cost method deduces the value of an environmental site by the travel cost of people who visit it.

3. Finally the constructed market approach directly asks the stakeholders how they would value the natural resource, for instance what they are willing to pay in order to avoid the destruction of the resource, or what they are willing to receive in order to avoid the destruction of the resource.

All these approaches are strongly criticized by some researchers of the ecological economics field (see for instance van den Bergh, 2001; Venkatachalam, 2007).

of the population level, i.e.  $n = f(P)$ . Let us assume there exists a maximum population level,  $L$ , at which the population of fish stops growing, i.e.  $f(L) = 0$ . If there is fishing, the population changes with the difference between the natural increase and the amount of fish caught in the sea” (Erreygers, 2014).

Then he adds the definition of a sustainable catch, with the effort level defined as the activity level of production of the Wild Tuna Method:

“a catch is sustainable if the effort level ensures that the population of fish remains constant. This means that, given the population of fish, the effort level is chosen in such a way that the catch  $c$  coincides with the natural increase  $n$ ” (Erreygers, 2014).

He constructs a model with five processes (corn production, wild tuna production, boats production, farmed tuna production and ponds production) and one basic good (corn). Given the actual demand and the population of tuna, he can define the activity levels of all processes. They should be such that the demand is answered and that the production can continue. On the price side, the rate of profit is uniform because “none of the available methods makes extra-profits” (Erreygers, 2014). The activity level of the method earning extra-profit is set to zero; given the rate of profit, it is possible to know the wage and the relative prices. This uniformity of the rate of profit is justified by Erreygers because he chooses to “focus on situations which correspond to the long term positions usually studied in classical theory” (Erreygers, 2014). The question he chooses to answer is: given a constant demand, is it possible to have constant prices and constant activity levels on one hand, and a sustainable catch on the other hand? He shows that this only possible for certain levels of demand.

#### 1.4.3.1 Discussion on Erreygers’ model

Erreygers thinks that his model would not be relevant if the sea were privately owned, but actually this is not true. In his model the sea has no owner, so no rent can arise on the sea. In case of tuna scarcity, rent arises on fisher boats. The logic goes like this: in order to satisfy the demand there are two options, to increase the effort level (by building new boats) or to produce tuna from aquaculture. The second method generates fishes with a higher price: then a rent is earned by the Catch in the Wild method. This rent is said to go in the boats owners’ pocket, because if there were enough boats, it would not have been necessary to develop aquaculture. Then scarcity is related in this case with a limited number of boats (and is called an “access-to-the-sea” scarcity by Erreygers). But as we saw in subsection 1.2.5, there is no need to find a limiting factor to observe the rise of a rent. Rent arises as soon as two processes producing the same good, with different profitabilities, are operated together. Then the distribution of the rent depends on institutional factors: fishermen would have earned the rent, if they were in a position to capture it, for instance.

And if the sea is privately owned, we are back to the case of land. If there is scarcity, then either it is possible to go on other “lands” (calling a “land” a privately owned part of the sea) and if other lands have a different productivity, an extensive rent arises. Or either it is possible to make aquaculture (at a higher cost). In that second case, a rent will also arise and the relations between landowners, boat owners and fishermen will decide how this rent will be distributed. So Erreygers’ model helps us to see that if there is a clear connection between the existence of two different processes producing the same output and rent, there is no clear connection between natural resources and rent, and between their private appropriation and rent.

Then Erreygers goes on saying that:

“The corn-tuna model therefore predicts that in a situation of growing demand the price of the renewable resource will steadily increase, until it reaches a steady equilibrium (the Good Scenario) or becomes unstable (the Bad Scenario). This may be thought of as a kind of Hotelling rule for renewable resources, but it must be kept in mind that the logic behind this rule is fundamentally different from the logic behind the Hotelling rule. The increase of the price of an exhaustible resource, such as guano in the corn-guano model, is explained by the profit-maximizing behaviour of the resource owners and occurs even when demand is not growing. In the corn-tuna model, by contrast, the price increase of the renewable resource is driven by a combination of biological and economic factors and occurs only when demand is growing” (Erreygers, 2014).

Firstly, it is not true that in Erreygers’ model, the price increases only when the demand is growing: if the catch is unsustainable and the demand stable, the catch per boat will decrease and the price of the tuna will increase. Secondly, why there should be a difference in the treatment between non-renewable resources and renewable resources? And if there should be no difference, shall we adopt the treatment of Erreygers (who shows that there can be an increase of the extracted commodity price, “driven by a combination of biological and economic factor”) or the Hotelling rule (driven by “the profit-maximizing behavior of the resource owner”)?

We can also find this problematic in Kurz (2006): he defines renewable resources as “resources capable of regenerating themselves provided the environment that nurtures them remains favourable”. The regeneration could be represented as follows:

$$u_{t+1} = u_t + f(u_t) \tag{1.69}$$

With  $u_t$  the size of the stock of the natural resource at time  $t$  and  $f(u_t)$  which could be positive or negative. It is especially negative when the extraction of the natural resource is higher than its natural replenishment. Then he acknowledges that, in this case, renewable resources becomes the equivalent of exhaustible resources. But, no matter if  $f(u_t)$  is positive or negative,

Kurz states that the price of the renewable resources is related with its cost of extraction: “the costs connected with the use of such resources are the costs incurred in raising them” (Kurz, 2006).

But when he talks about exhaustible resources, defined as “resources that are available in given stocks that cannot be increased” (Kurz, 2006), he assumes that if the resource gets exhausted, i.e. if  $f(u_t)$  is negative, the price of the resource will have to increase over time. He justifies this assumption by introducing the Hotelling rule: in a competitive economy, the storing of the resource “cannot be operated” if the ruling rate of profit is not earned by the owners of the exhaustible resources. Then there is clearly a logical problem: why the owners of renewable resources do not claim for a royalty the year the stock is depleted? Or, in return, why someone should ask for a royalty just because he owns an exhaustible resource, without any relation with the cost incurred in extracting the resource?

Following Gibson idea and Erreygers’ model, we see that there is no clear separation between a renewable natural resource and an exhaustible one. Fishes in the sea are renewable as long as the catch is equal or below the increase of population. This definition may apply to all natural resources. For example with oil: in this case, the increase of the oil stock is so slow that we could say that it is close to zero. Then the sustainable catch for an exhaustible resource like oil is also close to zero.

Erreygers introduces a relation between the catch and the effort level: the former is equivalent to an extraction rate while the latter is equivalent to a cost of extraction. So each natural resource can be defined by a stock (population  $P$  in the case of fish), a sustainable catch ( $c^*(P) = g(P, e^*(P))$ ), with  $e(P)$  the effort needed to achieve the catch) and an actual catch ( $c = g(P, e)$ ). If the actual catch is higher than the sustainable catch, the natural resource is exhausted. Otherwise, the resource may still be called renewable<sup>34</sup>.

#### 1.4.3.2 A simplified version of Erreygers’ Corn-Tuna model

Let us construct a simplified version of Erreygers’ model. There are three processes: a corn production process producing corn with corn and labour, a Wild Tuna Method producing tuna with corn and labour and a Farmed Tuna Method producing tuna with tuna, corn and labour. The three processes are described in table 1.4, with  $a_{ij}$  the input coefficients and  $b_{ij}$  the output coefficients, all coefficients being positive:

For the Wild Tuna Method, the stock of tuna in the sea depends on fishery and on population dynamics. The relation between the increase of population  $n$  and the population level of tuna in the sea  $P$  is described by equation 1.70:

$$f(P) = k_1 P(L - P) \tag{1.70}$$

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<sup>34</sup>It should be noted that depending on the population function and the catch function, there may be constant returns to scale or not. In the case of Erreygers’ model, there are not. But that shall not be a problem in the New Interpretation of Sraffa, as it is recalled than Sraffa is not making any assumption on returns to scale in *PCMC*.

Table 1.4: Processes in the simple Corn-Tuna Model (simplification from Erreygers, 2014)

Inputs					Outputs	
	Corn	Tuna	Labour		Corn	Tuna
Corn process	$a_{11}$	0	$l_1$	→	$b_{11}$	0
Wild Tuna Method	$a_{21}$	0	1	→	0	$b_{22,t}(P_t)$
Farmed Tuna Method	$a_{31}$	$a_{32}$	1	→	0	$b_{32}$

With  $L$  the maximum population level; the maximum sustainable yield is equal to  $k_1 \left(\frac{L}{2}\right)^2$ . The relation between the catch per fishermen and the population  $P$  is described by equation 1.71:

$$b_{22,t}(P_t) = k_2 P_t \quad (1.71)$$

With  $k_1$  and  $k_2$  two positive constants. These two equations are the same than in Erreygers' model (Erreygers, 2014; Schaeffer, 1954; Gordon, 1954). The whole catch, defined as the catch per fishermen multiplied by the activity level of the Wild Tuna Method (equal to the number of employed fishermen), is sustainable if it is lower or equal to the increase of population:

$$y_{2,t} b_{22,t} \leq k_1 P_t (L - P_t) \quad (1.72)$$

Then the maximal number of fishermen is defined by relation 1.73:

$$y_{2,t}^{max} = \frac{k_1 L}{2k_2} \quad (1.73)$$

Then we can follow Erreygers saying that “any catch below the maximum sustainable yield can be sustained either by a large population (and hence a low effort level) or by a small population (and hence a high effort level)” (Erreygers, 2014).<sup>35</sup>

The quantity equations are then:<sup>36</sup>

$$y_{1,t} b_{11} = y_{1,t} a_{11} + y_{2,t} a_{21} + y_{3,t} a_{31} + d_{1,t} \quad (1.74)$$

$$y_{2,t} b_{22,t} + y_{4,t} b_{32} = y_{3,t} a_{32} + d_{2,t} \quad (1.75)$$

With  $d_{1,t}$  and  $d_{2,t}$  the net demands for corn and tuna in period  $t$ ,  $y_{1,t}$  the activity level of the corn process and  $y_{3,t}$  the activity level of the Farmed Tuna Method, equal to the number of employer farmers.

<sup>35</sup>Hence there is two possible equilibrium: the first (large population) is stable because if there is a slight increase (reciproc. decrease) of the catch, the increase of population will be bigger (reciproc. smaller). The second equilibrium is unstable.

<sup>36</sup>Here I do not follow Erreygers, because he is going away from an analysis of a system in one moment of time, writing that outputs must be equal to the sum of aggregate inputs of the next period and net demand of the current period.



If the activity levels of the two processes of tuna production are both strictly positive ( $y_2 > 0$ ,  $y_3 > 0$ ), a rent has to occur. Here we touch a very important point: we have two methods producing the same good, with different productivities, so a rent must arise. But who should earn the rent? Should it be the workers, an hypothetical sea owner, an other agent? Here exchanges cannot help to decide how to write the equations, because it depends on local institutions.

Let us assume the following institutional framework:

- the sea is not privately owned so there could be no rent on the sea.
- the workers are in position to capture the rent if both methods of producing tuna are used.

Besides that, corn is the numeraire ( $p_{1,t} = 1$ ,  $\forall t$ ), and the profit rate  $r$  is defined in an exogenous way constant and uniform.

The price equations are then, with wages paid after the production process:

$$b_{11} = (1 + r) a_{11} + l_1 w \quad (1.76)$$

$$b_{22,t} p_{2,t} = (1 + r) a_{21} + w + y_2 \rho_t \quad (1.77)$$

$$b_{32} p_{2,t} = (1 + r) (a_{31} + a_{32} p_{2,t}) + w + y_3 \rho_t \quad (1.78)$$

With  $p_{2,t}$  the tuna price,  $w$  the wage, and  $\rho_t$  the rent on labor (if  $y_{3,t} = 0$  or  $y_{2,t} = 0$ ,  $\rho_t = 0$ ).

If  $y_{3,t} = 0$ , we have a Wild Tuna System. If  $y_{2,t} = 0$ , we have a Farmed Tuna System. As both systems have the same standard system, the wage rate is the same in both of them. Then it is possible to compare the price of the tuna produced in both cases (the cheapest tuna produced reveals the better system). There is finally a possibility that both techniques are used at the same period, the Mixed Tuna System: in that case the cheapest technique earns the majority of the rent. Thus there is a possibility that the Farmed Tuna Method captures the majority of the labor rent if the method is cheaper than the Wild Tuna Method.

In all cases, the wage is given by:

$$w = \frac{b_{11} - (1 + r) a_{11}}{l_1} \quad (1.79)$$

Then, if we observe a Wild Tuna System, the price of tuna is:

$$p_{2,t}^W = \frac{1}{b_{22,t}} \left[ (1 + r) a_{21} + \frac{b_{11} - (1 + r) a_{11}}{l_1} \right] \quad (1.80)$$

If we observe a Farmed Tuna System, the price of tuna is:

$$p_{2,t}^F = \frac{1}{b_{32} - (1 + r) a_{32}} \left[ (1 + r) a_{31} + \frac{b_{11} - (1 + r) a_{11}}{l_1} \right] \quad (1.81)$$

Finally if we observe a Mixed Tuna System, we have two equations (1.77 and 1.83) with two unknowns ( $p_{2,t}$  and  $z_t$ ). This can be solved:

$$\rho_t = \frac{b_{22,t} [(1+r)a_{31} + w] - [(1+r)a_{21} + w] [b_{32} - (1+r)a_{32}]}{y_2 [b_{32} - (1+r)a_{32}] - b_{22,t}y_3} \quad (1.82)$$

$$p_{2,t}^M = \frac{(1+r)a_{21} + w + y_2\rho_t}{b_{22,t}} \quad (1.83)$$

If we want a positive rent and if  $\frac{[b_{32} - (1+r)a_{32}]}{y_3} \geq \frac{b_{22,t}}{y_2}$ , i.e. if the Farmed Tuna Method is more productive than the Wild Tuna Method, then we need that  $\frac{[(1+r)a_{31} + w]}{[b_{32} - (1+r)a_{32}]} \geq \frac{[(1+r)a_{21} + w]}{b_{22,t}}$ , i.e. we need that the input costs per unit of output are higher in the Farmed Tuna Method (this is coherent with the way Sraffa describes intensive rent, Sraffa, 1960, § 87). Then if these conditions hold, the derived function of the rent  $\rho_t$  along  $b_{22,t}$  being positive, the rent will increase if the population of tuna is increasing. Similarly we can see that if the activity level of the Wild Tuna Method increases, the rent goes down and if the activity level of the Farmed Tuna Method increases, the rent goes up.

### 1.4.3.3 A numerical example

Now let's have a numerical example.

Table 1.5: Processes in the simple Corn-Tuna Model - numerical example (simplification from Erreygers, 2014)

Inputs				Outputs	
Corn	Tuna	Labour		Corn	Tuna
2	0	1	→	10	0
1	0	1	→	0	$b_{22,t}(P_t)$
1	1	1	→	0	10

Wage is now always equal to:

$$w = 8 - 2r \quad (1.84)$$

If we observe a Wild Tuna System, the price of tuna is:

$$p_{2,t}^W = \frac{9 - r}{b_{22,t}} \quad (1.85)$$

If we observe a Farmed Tuna System, the price of tuna is:

$$p_{2,t}^F = 1 \quad (1.86)$$

Finally if we observe a Mixed Tuna System, the price of tuna and the rent are:

$$\rho_t = \frac{(b_{22,t} - 9 + r)(9 - r)}{y_2(9 - r) - y_3 b_{22,t}} \quad (1.87)$$

$$p_{2,t}^M = \frac{9 - r + y_2 \rho_t}{b_{22,t}} \quad (1.88)$$

These results depend on the catch function. Suppose that we have  $k_1 = 1/100000$  and  $k_2 = 1/1000$ , with a maximum population of  $L = 20000$ . Then the average catch per worker is  $b_{22,t} = P_t/1000$ . So if the Wild Tuna Method is used, and if the tuna population is decreasing, the catch per fisherman will decrease and the price of tuna will increase. There is no Hotelling rule involved, no equilibrium either, this is just a technical relationship between the physical data.

Then there is two possibilities.

1. Either the level of activity  $y_2$  is such that the catch is below or equal to the sustainable catch  $c_t^* = P_t(20000 - P_t)/100000$ . For instance, if  $P_t = 15000$ , we have  $c_t^* = 750$ . Then the maximum activity level is  $y_2 = c_t^*/b_{22,t} = 50$ . If the amount of fisherman is equal or lower than 50, the resource is renewable. As an example, if the amount of fisherman is  $y_2 = 30$ , in the next period, population of tuna will be equal to  $P_{t+1} = P_t + k_1 P_t(L - P_t) - y_2 k_2 P_t = 15300$ . If the Wild Tuna Method is the only method used, with constant level of activities and a constant rate of profit, the price of tuna will be lower in the next period. For instance, with  $r = 10/100$ , we have  $p_{2,t}^W = 89/150 \sim 0.59$  and  $p_{2,t+1}^W = 89/153 \sim 0.58$ . If we observe a Mixed Tuna System, the rent counterbalances the decrease of the price. If  $y_3 = 1$ , we have  $\rho_t = 5429/25200 \sim 0.22$  and  $\rho_{t+1} = 5696/25170 \sim 0.23$  and the price of tuna increases slightly:  $p_{2,t}^M = 2581/2520 \sim 1.024$  and  $p_{2,t+1}^M = 43877/42789 \sim 1.025$ . This movement of population, price and rent will come to an end when the population reaches its maximum level, i.e. when  $P_\infty = L$ . Then the price of tuna will be in the Wild Tuna System equal to:  $p_{2,\infty}^W = 89/200 = 0.445$  and in the Mixed Tuna System the rent will be equal to  $\rho_\infty \sim 0.4$  and the price of tuna equal to  $p_{2,\infty}^M \sim 1.045$ .
2. Or the level of activity is unsustainable, i.e. higher than the sustainable one. As an example, with  $P_t = 15000$ , the catch is set to  $c_t = 1500$ . Then the activity level is  $y_2 = c_t/b_{22,t} = 100$  and in the next period, population of tuna will decrease to  $P_{t+1} = 14250$ . If the Wild Tuna Method is the only method used, all other things being constant, the price of tuna will be higher in the next period. For example, with  $r = 10/100$ , we have  $p_{2,t}^W = 89/150 \sim 0.59$  and  $p_{2,t+1}^W = 890/1425 \sim 0.62$ . If we observe a Mixed Tuna System, the rent counterbalances the increase of the price. If  $y_3 = 1$ , we have  $\rho_t = 5429/87500 \sim 0.06$  and  $\rho_{t+1} = 9523/175150 \sim 0.05$  and the price of tuna slightly decreases:  $p_{2,t}^M = 8811/8750 \sim 1.007$  and  $p_{2,t+1}^M = 334818/332785 \sim 1.006$ . This movement of population, prices

and rent will come to an end if the increase of the population becomes equal to the catch, i.e. when  $k_1 P_t (L - P_t) = y_2 k_2 P_t$ . In our case, the population will decrease until  $P = L/2$ , and then will be kept at this level. At this level the price of tuna will be in the Wild Tuna System equal to:  $p_{2,\infty}^W = 89/100$ ; in the Mixed Tuna System the rent will be equal to  $\rho_\infty \sim 0.011$  and the tuna price equal to  $p_{2,\infty}^M \sim 1.001$ . But there is the possibility that the number of fishermen is so high that the increase of tuna population will never be equal to the catch: this occurs when  $y_2 \geq 200$ . In this case, the population will decrease until there is no more tuna in the sea. But as it will be harder and harder to find it, the Farmed Tuna Method will become more and more profitable: and at one level of population the rent becomes equal to zero, and then becomes negative when the majority of the rent is won by the Farmed Tuna Method. This turning point occurs when the price of the Wild Tuna becomes equal to the price of the Farmed Tuna, i.e. in our case when  $b_{22,t} = 9 - r$ ; the population level at the turning point is equal to:  $P_t = \frac{9-r}{k_2} = 8900$ .

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