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Three Examples of Avoidable Confusion

F. LAROUI[1] AND B.C.C. VAN DER ZWAAN[2]

[1]EPCEM, Institute for Environmental Studies (IVM), Vrije Universiteit, Amsterdam, The Netherlands, and [2]Energy research Centre of the Netherlands (ECN), Policy Studies Department, Amsterdam, The Netherlands

ABSTRACT

Nature, *natural resources*, *reserves*, *raw materials*, these are notions common to a number of different disciplines: geophysics/geology, economics/ecology and environmental/energy studies. There is manifestly a risk of confusion regarding their precise meaning, when one switches from one discipline to another, in the same way as their definition can change from one author to another, or even from one language to another. In interdisciplinary or multidisciplinary research, much misunderstanding vis-à-vis the wording used can be avoided by employing strict definitions. Therefore, a clear characterisation and delineation of concepts, as well as transparent statements on the relations that link them, is a prerequisite to any fruitful discussion between researchers from different disciplines. In this paper, we suggest precise definitions for the concepts *nature*, *natural resources*, *reserves* and *raw materials*. Using these definitions, and interpretations of the interactions between them, we give three examples that show that semantics matter. The examples are taken from the increasingly important field that researches global and regional environmental problems, *par excellence* an area characterised by inter- and multidisciplinarity. The proposed definitions and the description of three cases in point provide the opportunity to discuss the recently emerged concepts of *renewability* and *sustainability*, today paramount terminology in environmental sciences.

Keywords: nature, natural resources, reserves, raw materials, renewability, sustainability.

1. INTRODUCTION

The concepts *nature*, *natural resources*, *reserves* and *raw materials* possess different meanings. In addition, their meaning can differ depending on the discipline in which they are used. In this paper, we provide precise definitions of these notions, in such a way that they can be used uniformly over the various disciplines from which environmental sciences draw. Also characterisations of the interactions between these notions are given, notably via three examples that show that semantics matter.

This article consists of two parts. In the first part, the concepts *nature*, *natural resources*, *reserves* and *raw materials* are defined, via a diagram that describes the relations between them. It is argued that the extent to which mankind interacts with nature determines which of these notions ought to be employed in a given context. The ideas underlying the diagram are clarified by alluding to the availability of oil resources, which in the world at present is an important determinant for societies to reach desirable levels of economic development and human welfare. Simultaneously, however, its large-scale use, by its combustion for energy production, constitutes one of the main threats to mankind in the 21st century, in terms of both local pollution and global warming, related to e.g., particulate and greenhouse gas emissions, respectively.

In the second part, three concrete examples are given, illustrating the importance of possessing workable definitions. Via these examples, it is shown that in multidisciplinary sciences, such as environmental studies, much confusion can be avoided by employing well-defined wording. The three examples are mostly related to three essentially different disciplines: physics, biology and chemistry. They are drawn from environmental-scientific queries related to, respectively, the availability of nuclear energy resources, the extent of land use requirements, and the ineluctability of human phosphate needs. We end with a number of conclusions and recommendations for scientific conduct in environmental sciences.

2. FROM NATURE TO RAW MATERIAL

Figure 1 depicts the diagram that will be used as our reference throughout both parts I and II of this paper.

Address correspondence to: Dr. Bob van der Zwaan, Energy research Centre of the Netherlands (ECN), Policy Studies Department, P.O. Box 37154, 1030 AD, Amsterdam, The Netherlands. E-mail: vanderzwaan@ecn.nl

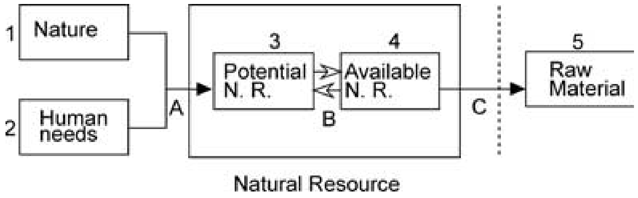

Fig. 1. From nature and human needs, through potential and available natural resources, to raw material.

Indicated are five stages that can be distinguished in going from *nature* (**1**) and *human needs* (**2**), via *potential* (**3**) and *available* (**4**) *natural resources*, to *raw materials* (**5**). Three transitions can be distinguished, in the order of increasing interaction of mankind with its natural environment: one from (**1**) and (**2**) to (**3**) and (**4**) (interaction **A**, with a passive human role), one between (**3**) and (**4**) (**B**, with an intermediate human role), and one from (**3**) and (**4**) to (**5**) (**C**, with an active human role).

Nature (or *natural conditions*) can be studied in connection with a large number of disciplines, among which geology, hydrology and climatology. Natural conditions precede all human needs and human activity. It is this feature that essentially distinguishes natural conditions from the notions natural resources and raw material, the latter two being the result of Man's interaction with nature. By their very definition, natural conditions are *not* an object of study of economics, or the social sciences in general, but merely of the natural sciences.

Human needs, on the other hand, *are* a subject of study of the social sciences. They are socially and economically determined. They follow from many kinds of social conditions, such as the level and characteristics of economic development, the technological state-of-the-art at a given time, and the prevailing social and cultural organisation of human society. It is their existence which 'creates' natural resources, and subsequently raw materials, from natural conditions.

Natural resources and *raw material* are thus doubly determined, on the one hand by natural conditions, and on the other hand by human needs, viz. the needs of the global society as a whole or some specific society in particular. They follow directly from the interaction between nature and human needs, and lose their meaning under the absence of either nature or human needs.

Relation A of the diagram must constantly be kept in mind, lest the concepts of natural resource and raw material lose their social and economic content and, in consequence, their temporal and spatial dimensions. It is relation A that brings economics in the picture, since the combination of human needs and the intrinsic limitation of natural conditions available on Earth introduces a *scarcity* constraint at this level.

Relation B determines the availability of natural resources for mankind. Within the category of natural resources, we must distinguish between two sub-categories: potential natural resources (in short, *resources*) and available natural resources (or *reserves*).[1] This distinction is necessary to proceed from (1) to (5). Indeed, the combination of 1 and 2 indicates among all natural elements those that can technically be used to satisfy a given human need. These are called resources. Subsequently, a whole range of factors, mainly economic, but also political or strategic, intervene and delimit the share of resources which at any given time can effectively be exploited. These are called reserves. Note that one could even classify further, and create an extra dimension in the diagram, by distinguishing between unknown, hypothetical, possible, expected and proven reserves.

Relation C denotes the passage from natural resource to raw material, and implies the contribution of factors of production, first among which is labour. The passage from natural resource to raw material, as well as the production factors and functions that are used herein, is the subject of extensive research and established literature in both micro- and macroeconomics. The essential difference between a natural resource and a raw material is that the former, in spite of its socio-economic content, still remains a gift of Nature, whereas the latter is a product of committed human activity.

Before describing the three cases of multidisciplinary confusion, we illustrate briefly the diagram of Figure 1 with an example, related to the availability in the Earth's crust of (large, but limited) reserves of oil. At many – geographically disperse – places, 'crude' oil is locked up in geological layers with certain geophysical properties, the precise amounts of which are largely unknown. Crude oil is thereby a natural condition, depicted by (1) in Figure 1. At present, one of mankind's many needs is oil, since economies currently thrive on the consumption of this fossil fuel in particular, predominantly in the field of transportation (2). The very existence of a (potential) natural oil resource is defined (or 'created') by the concurrence of nature and the human need of a fuel for transport (3). The costs of such activities as the exploration of oil reservoirs and their drilling to get crude oil to the surface, as well as the existence of technologies available to allow e.g., the exploitation of reservoirs at increasingly larger depths, determine the oil reserves currently available (4). Crude oil ought to be refined and treated in order to allow its use for a variety of applications, such as petrol in cars and kerosene in aeroplanes (5).

Because of the diversity of factors that delineate resources from reserves, passage B is possibly the most dynamic part of the diagram in Figure 1. Whereas passages A and C are relatively straightforward to interpret, the multitude of relevant factors affecting B renders this passage also perhaps the most difficult to comprehend. One can probably best understand reserves as constituting a subset of total natural resources of a given kind. A given physical

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[1] Note that in French this terminology is employed inversely: *resources* are reserves, and *réserves* are resources.

quantity of natural condition can pass *in situ* from the category resources to reserves, following economic, political or strategic fluctuations. As a result, reserves are partly determined by the economy, both potentially negatively and positively: reserves can constitute a larger or smaller part of total resources according to a variety of economic conditions.[2]

Two important (interrelated) economic conditions, in this context, are prices and the prevailing technological state-of-the-art. The boundary between total resources and 'proven' reserves fluctuates with the relationship between fuel prices and extraction costs. Reserves can only be ascertained by drilling, which is an expensive activity, so the reserve boundary is restricted by the expenditures that oil companies are willing to make in order to justify their investments. Oil prices are subject to fluctuations on the oil market. If prices offered at oil markets increase, the amounts of oil recoverable for that price (hence, the reserves) become larger.[3] Modifying economic and geo-strategic conditions or changing legal and fiscal provisions, as well as the geological properties of the site an oil company decides to drill, affect its choices regarding exploitation activities. If extraction costs decrease, sites that were previously uneconomic can become worth drilling, so that available oil reserves increase. Inversely, unabsorbed cost increases can cause these reserves to shrink.

Reserves are augmentable by steered technical improvements. As more techniques to explore and drill oil reservoirs become available, oil resources that were initially inaccessible become exploitable, so that oil reserves are enhanced. Technological change plays an important role in oil reserve forecasting. Controversy exists as to how long mankind will be able to rely on oil during the 21st century, precisely because of the question whether these predictions account for technological improvements or not. A growing contingent of geologists warns that oil will begin to run out in one to two decades from now, that is, around 2010–2020 the gush of oil from wells around the world will peak at some 80 million barrels per day and then begin a steady inevitable decline [1]. Their predictions are based on bell-shaped curves applied to world oil production, employed successfully to American oil well production in the 1950s by the geologist Hubbert, who formulated what seemed to be a fundamental law governing the exploitation of a finite resource – that production will rise, peak and then fall. These predictions are subject to controversy as to whether or not the used curves account for technological change, which one is likely to experience in the future [2]. Whereas pessimists claim that Hubbert's curves already incorporate steady technological development, the optimists state that any concept of reserves, such as the one designed by Hubbert, is inherently backward-looking and conservative, and therefore insufficiently represents the expected oil reserves that are likely to be available. Today, forecasts concerning the exhaustion of a given natural resource, oil in particular, are mostly made at the reserve level. The above discussion shows that such forecasts have an uncertain basis. That uncertainties prevail is also demonstrated by the mere variety of figures that appear on the supposed future availability of natural reserves (see, for example, [3]). Even if we suppose that oil reserves constitute a stock given once and for all – corresponding to the *glob* of Baumol and Oates [4][4] – any forecast arrived at by dividing that stock by the current oil extraction rate is subject to caution. Indeed, there is no reason to suppose that the extraction rate itself or, for that matter, the consumption rate, will not change.

Note that the "life-cycle theory of mineral raw materials" does not use a flow chart similar to the one represented in Figure 1. According to this theory, products derived from mineral resources go through four phases of development: youth, maturity, senescence and decline. One of the postulates of the theory is that the perspective of the exhaustion of the natural resource determines the last two phases. The large deficit of this theory, however, is that the concept natural resource is used without any precision, that is, without taking any of the above-mentioned economic aspects into account. It has been conclusively shown that no mineral raw material shows such a life cycle [5]. Humphreys argues that resource behaviour is not directly related to the level or rate of production, but is rather determined by the complex interaction of production, price and demand. He states that "the unpredictability of this interaction (...) makes it difficult to attach any meaning to the idea of a constant 'ultimate' resource."

As a final remark with respect to Figure 1, note that, for reasons of clarity and exposition, the diagram does not represent or depict the potentially detrimental effects that human activity can have on nature. It is important to realise, however, that natural conditions are generally not left unharmed by human activities on Earth. Quite on the contrary, as is commonly known today: the current discussion on global climate change, for example, finds its origin in Man influencing with its activities the natural properties of the Earth's atmosphere. Also, in the case of e.g., global fish populations, Man has clearly been able to increase reserves (by improving fishing techniques), but is at present also decreasing resources (by polluting seas and oceans, and through over-fishing). Hence, human needs 'create' resources from natural conditions, but human activity or requirements can equally destruct natural conditions.

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[2] Note that the distinction between resources and reserves becomes tricky when one considers a by-product of the exploitation of some other product.

[3] Note that it is only in a market economy that reserves can be identified, because reserves depend on prices that reflect the conditions of production. In planned economies such prices are (were) often absent.

[4] Baumol and Oates ([4], p. 139).

3. THREE EXAMPLES OF MULTIDISCIPLINARY CONFUSION

3.1. Case 1: Nuclear Energy Resources

Our first example relates to nuclear energy. An inquiry into this energy source's availability demonstrates well that ample confusion can emerge when natural and social scientists jointly analyse this subject matter, notably between physicists and economists. This is probably a result of the technicality of many aspects of nuclear energy, but surely also the result of a lack of clear definitions. Since physicists are likely to refer to 'resources' and economists to 'reserves,' the former (having more direct access to understanding physical theory and nuclear technologies) can quote figures on the availability of nuclear energy that exceed those referred to by the latter (viewing the matter from a more practical and economic perspective) by even orders of magnitude. Indeed, physicists often tend to claim that mankind possesses access to nuclear energy for still many centuries to come, or even millennia, whereas economists usually state that nuclear reserves will last for about only another half a century under present rates of uranium consumption. Hence, to avoid semantical problems, it is quintessential to come up with definitions that cover all of nuclear energy's peculiarities.

Nuclear energy faces many obstacles, the most persistent among which are radioactive waste, nuclear proliferation, and reactor accidents. Whereas nuclear energy has proved to be able to compete with its fossil fuel counterparts, it generally faces difficulties constituting an economically attractive energy alternative. Probably the most pertinent problem, and also perhaps the most difficult to solve, is not technical or economic in nature, but relates to the unfavourable public opinion of nuclear energy. Yet there remains one powerful factor in favour of nuclear energy: global warming (see, for example, [6]). During reactor operation, nuclear energy does not emit carbon dioxide or other greenhouse gases. Global warming and the required transformation of world energy supply and consumption is probably becoming one of the main challenges mankind will face during the 21st century, and is therefore subject to both extensive academic and policy-related studies (for an economic analysis of climate change, see [7]). One of the main difficulties in thinking about the advantages and disadvantages of nuclear energy is the issue of (economic) discounting and intergenerational equity (for an overview of the latter, see [8]). Both nuclear energy's merits, in the sense that it can contribute to reducing carbon emissions, and drawbacks, such as the production of radioactive waste, possess long time horizons (from centuries to millennia, or even more), which renders it difficult to value and compare them properly.

The case of nuclear energy, and the availability of nuclear energy resources, illustrates well the dichotomy between resources and reserves. The nuclear 'natural condition' is the availability, in large (but limited) amounts, of the element uranium in the Earth's crust. Natural uranium, that is, uranium as it occurs in its natural condition (the 92nd element of the periodic table of chemical elements) consists of two isotopes. While uranium nuclei consist always of 92 protons, they can possess different numbers of neutrons. We thus have two types of uranium, uranium-235 and uranium-238, the number indicating the total amount of particles (protons or neutrons) in the uranium nucleus. Uranium-235 is the only naturally occurring isotope that is fissile, meaning that it can break up in several parts in the presence of thermal (low energy, or slow) neutrons.[5] Under special conditions, uranium containing a sufficient share of uranium-235 (typically 3–4% in nuclear reactors, whereas this share is 0.7% in nature, and exceeding 90% in nuclear weaponry) can sustain a chain of nuclear fission reactions. This chain reaction constitutes the basis for the production of nuclear energy (for a further treatment of the technical basics of nuclear energy, see [9]). It is fundamental to realise that if uranium were only to exist naturally as one isotope, uranium-238, the natural condition of uranium would remain intact, but nuclear energy as an energy resource would be non-existent. Hence the importance of both understanding the scientific aspects of nuclear energy and of possessing appropriate definitions, of 'natural condition' and 'resource' in this case.

Passages A and C are relatively straightforward to characterise for nuclear energy. When fission was discovered in the early 1930s, it was soon realised that it could provide mankind with large amounts of energy. Meanwhile, mankind was radically increasing its need for energy, an evolution that proceeded during the entire 20th century. Thus, in terms of the terminology employed in passage A of our diagram, the combination of increasing human energy consumption and the scientific discovery and technological development of power produced from nuclear fission processes 'created' new energy resources, complementing the existing resources of traditional and fossil fuels. Hence, the energy resources available on Earth were extended significantly by the discovery of nuclear energy. Passage C for nuclear energy involves the fabrication of nuclear fuel that can be used in reactors. Nuclear fuel fabrication is rather complex, and involves more steps and more advanced technological equipment than the refinery procedures required for fossil fuel use. The production of nuclear fuel involves such processes as uranium mining, uranium from ore extraction, conversion, enrichment and fuel rod fabrication. Passage C for nuclear energy also requires more intensive and more specialised labour, not readily accessible for many countries in the world, than is the case for its fossil fuel counterparts.

The description of passage B for nuclear energy sheds some interesting light on the interpretation of Figure 1's diagram, and the role of technologies herein. Nuclear energy

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[5] Note that no other isotope in nature possesses this fission property.

reserves have increased considerably over the past decades, via a number of technological developments. As a result of the discovery of numerous profitable mining sites, uranium reserves increased rapidly during the first decades after the discovery of fission. The technologies for recovering uranium from natural uranium ores have improved over time, allowing concentrations of uranium in ore that are today smaller than those before. This evolution has extended considerably the uranium reserves available for energy use.[6] Two further tendencies exist that may extend nuclear reserves in the future. First, it has been shown that an additional element, thorium, can be employed suitably as nuclear fuel in reactors. Initially, the use of thorium was not seriously contemplated because of the absence of any naturally occurring fissile thorium isotope. Today, however, with large existing stockpiles of fissile material (partly resulting from Cold War era military complexes and originating from the dismantling of American and Russian nuclear weapons), as well as with the possibility to generate fissile materials by specially designed nuclear reactors, thorium has become a realistic option to be used as an additional fuel in reactors. Second, the development of breeder technologies (so-called 'fast neutron reactors') allows extending nuclear energy reserves by at least an order of magnitude. Whereas in conventional reactors only about 1% of the natural nuclear material is 'burned,' breeders allow using a much higher share, since they are capable of producing fissile material while simultaneously burning some. Interestingly, breeders were developed in a time that uranium reserves were thought to soon become scarce and uranium fuel expensive, and as a response to the oil shocks of the 1970s. Today, however, breeders are economically not interesting enough, and uranium reserves are expected to be large at low fuel prices. Still, in the future breeders might regain interest, since they can provide, by any common standard, virtually infinite energy reserves.

The above shows that without a multidisciplinary explanation of nuclear energy's characteristics on the one hand, and without a proper definition of the terminology vis-à-vis resources and reserves on the other hand, the discrepancy between the numbers scientists from different disciplines quote regarding nuclear energy's availability is understandable. Through lucid definitions lots of confusion can be avoided.

3.2. Case 2: Land Use Requirements

Our second case focuses on human land use requirements. Below, we address the question 'What is land?', while simultaneously the question 'What does *renewable* mean?' is assessed. Non-renewability is a fuzzy concept, which is often wrongly used and lies at the root of much confusion. It is on this concept, however, that rest most of the forecasts of imminent natural resource exhaustion that have periodically been cropping up for at least a century. As early as 1865, Stanley Jevons predicted the end of the Industrial Revolution in Great Britain on account of the exhaustion of coal (cf., for example, [10]). Since then, these alarms have not ceased, culminating with the publication of the report of the Club of Rome. Most of these predictions are questionable and often not comparable amongst each other, partly because the terminology used is not properly defined, or the concepts employed come from entirely different disciplines.

Let us take for instance the seemingly straightforward question 'Is land renewable?' or, even shorter, 'What is land?' The answers are less obvious than might seem. The word 'land' is common to different sciences: geology, economy, ecology, etc. There is a risk of confusion, when it is used without any explicit reference to the context in which it is employed. To see why, let us take the following discussion (see, [11])[7] (we have italicised some parts): "If we ignore the act of extraction as a production activity, [an exhaustible resource] is among the class of non-produced goods (i.e., it is a primary commodity). *But then*, *so is agricultural land*, and we do not usually regard land as being exhaustible in the same way as fossil fuels are. The distinguishing feature of an exhaustible resource is that it is used up when used as an input in production and at the same time its undisturbed rate of growth is nil. In short, the intertemporal sum of the services provided by a given stock of an exhaustible resource is finite. *Land*, *if carefully tilled*, *can in principle provide an unbounded sum of services over time*. This is the difference."

The problem here is that the word 'land' is not defined. The authors may have thought that a common and trivial word such as 'land' needs no definition. What is more obvious than land? However, the whole argument is semantically flawed, precisely as a result of the confused usage of that word. If one uses 'land' in a discussion based on purely economic arguments – such that 'land,' for instance, can be associated to Ricardian rents – one can stay at a level of generality where 'land' is an intuitive concept that does not have to be explained any further. However, the authors try to compare land and fossil energies as inputs of the production process. They should, therefore, make their entire analysis, including the definition of the terminology employed, at the more detailed level of the act of production itself. But they don't.

To illustrate this further, we design a simple (tale-telling) experiment, which does go down to the level of precision required. Suppose a bucket is filled with rigorously insoluble crystals, quartz for instance. Water and fertilisers, such as the chemical substances K_2O and P_2O_5, are added, as well as

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[6] In the future, reserve extensions can be expected if it becomes profitable to gain uranium from seawater. Recent technological developments in uranium from seawater extraction have been such that this could once be both technically feasible and economically interesting.

[7] Dasgupta and Heal ([11], p. 153).

nitrogen and a number of certain 'oligo-elements.' In this bucket, one can now, in principle, grow any plant one wishes. Obviously, the insoluble crystals play strictly speaking no role, since the plants in the bucket only absorb materials in solution. Now, the semantics question that poses itself is 'What is land in this experiment?' Three observations in relation to this question can be made.

I. If we reduce the meaning of the notion 'land' to that of 'insoluble crystals,' or more generally to that of all the elements that basically play no role in the growth of plants, then 'the intertemporal sum of the services provided' is nil. This does not seem what Dasgupta and Heal had in mind in their attempt to define exhaustible resources and compare the notions land and fossil fuels.
II. If we define 'land' as 'everything that is in the bucket' – as do implicitly all authors who study the economic aspects of land – then 'the intertemporal sum of the services provided' is necessarily limited. The reason is simply because plants will eventually have absorbed all the useful elements in the bucket, in such a way that the capacity of land to generate plants will be exhausted.
III. If the phrase 'if carefully tilled' means that chemical elements will be re-introduced in the bucket as soon as they are absorbed by the plants, then the question of the renewability of land is rigorously equivalent to that of its useful elements. In terms of plants being able to absorb these elements, and subsequently grow, K_2O and P_2O_5 can then be considered of the same type as fossil fuels.

Therefore, in spite of what Dasgupta and Heal write, there is no real difference between non-renewable resources such as fossil fuels and the specific example of land, that is, in the second and third meaning of the word. If we are talking about reserves, their growth rate can be positive, nil or negative, depending on the economic conditions of the moment. If resources are considered, however, the concepts renewability and reproducibility must be taken in their geologic meaning, and the temporal horizon must be indicated. On a human scale, resources are strictly limited, and their use can only imply a negative growth rate. No mineral raw material is therefore really renewable: it is non-renewable and non-reproducible. On such a scale, land is also a non-renewable resource, as our thought experiment shows.

If we were to expand our diagram with the concepts non-renewability and non-reproducibility, where in the diagram should we depict them? The preceding discussion leads us to answer: neither at the raw material level, nor at the reserve level. We must go one step further to the left, that is, to the level of potential natural resources. But we are then burdened with a concept that has no real practical use: the concept land is hereby reduced from its usual economic meaning (to the very right of the diagram) to a rather geological or chemical meaning (more to the left of the diagram). In the next example, it is shown that a potential natural resource, which is non-reproducible like fossil fuels and land, can also be seen as 'invariant.' The confusion can be fully solved only if the concepts 'concentration' and 'dilution' are introduced.

3.3. Case 3: Human Phosphate Needs

As last natural resource example, we analyse mankind's ineluctable needs of the chemical substance phosphate. While doing so, we address the concept *sustainability*, which has become fundamental in studying environmental problems over the past decade. Many definitions of sustainability have been proposed (see, for example, Boulding, 1991; [12]).[8] On the political level, it seems that *sustainable development* is just a simple way of saying "*economic* development which is *ecologically* sustainable." In the seminal Brundtland report [13], we find one definition only: "sustainable development is development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs."[9] Several different paragraphs of the same report, however, propose different approaches, some of which are controversial.[10]

The sustainability discussion in our context can be best delimited by asking: How can we manage natural resources in a sustainable-development perspective? Some authors propose a two-step approach. In this approach, first a standard or norm is determined of the annual consumption of natural resources that is required to avoid exhaustion, independently of any economic optimisation. Second, this norm is adhered to at the lowest possible economic cost (see, e.g., [14]).[11] This approach seems legitimate when it comes to forests or livestock, but less obvious for animal species.[12] But how should we manage minerals, which are also natural resources? Other related questions arise, such as: Is it possible to determine a norm independently of any economic optimisation?; Is it possible to determine a common norm?; and What precise meaning can be attached to the word exhaustion?

With our third example, relating to the human needs for phosphate, we want to show that using the same word (exhaustion) for living organisms and natural resources leads

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[8] A very general discussion of the concept sustainability can be found in Boulding (1991, p. 23). A more detailed and recent one can be found in Goodland and Daly [27]. Note that the idea existed before the word gained currency. For instance: "Conservation (. . .) takes on meaning only through defect. The idea would have no point in a society which maintained a favourable and *well-balanced relation to its environment*." (Quoted in Williamson, *op. cit.*, p. 97).

[9] World Commission on Environment and Development ([13], p. 43).

[10] *Op. cit.* pp. 43–46.

[11] Faucheux [14]. See also Baumol and Oates ([15], pp. 42–54) and chapter 11 in Baumol and Oates [4].

[12] For an analysis of the substitutability properties between man-made and environmental goods, notably regarding forests, livestock, species and biodiversity, see Neumayer [16] and Gerlagh and van der Zwaan [17].

to confusion. The two disciplines concerned, biology and geology, may use the same word, but the concept itself is clearly defined only for biology. As a matter of fact, the concept is even meaningless in geology, unless qualified by other concepts, such as concentration, dilution and energy use.

Thus, instead of extensively eliciting one particular definition of sustainability or sustainable development from the literature, we try to adopt the reverse approach. We start with a given natural resource, and subsequently analyse its physical and chemical properties, to see what these characteristics tell us about sustainable development. We take phosphate as a concrete example of a natural resource, because it has some interesting properties that allow us to answer some of the questions posed above. Let us trace its path in the diagram of Figure 1. In nature (1) a chemical element exists, phosphorus, of which humanity has a vital need (2). Scarcity appeared only relatively recently (passage A).[13] The Earth carries large amounts of phosphorus resources (3). Reserves (4) are today mainly determined by extraction costs, that is, in the absence of political or strategic constraints (passage B). The raw material (5) is tricalcic phosphate $Ca_3(PO_4)_2$, diluted with a certain amount of lime and other impurities (passage C).

If we attempt to apply the two-step approach, we are confronted with a number of problems. Is it possible to determine a norm independently of any economic optimisation, when the delineation between natural resources and reserves is intrinsically charged by economic concepts? The only way to avoid economics would be to go as far as possible to the left of our diagram and conduct the discussion at the level of natural conditions. What does this imply in the example of phosphate? The sole purpose of phosphates is to bring phosphorus to plants. If avoiding economics implies going to the very left of our diagram, we might as well remove passages A, B and C from it entirely. Hence, we might better base our discussion on the mere presence of that element, in any form and at any concentration, in the Earth's crust and oceans. But then the norm problem simply vanishes, according to Lavoisier's principle: annual consumption is allowed to be *infinite*, since phosphorus never actually disappears. However much is consumed by mankind and its (agricultural) activities, the total amount of phosphorus on Earth is constant.

In order to tackle the exhaustion problem, we have to find a way of introducing a *finite* norm. To establish such a finite norm, we have to move away from the left-hand side of our diagram. We could still avoid entering the rectangle (where economic conditions begin to operate) by adding an additional constraint, at the level of relation A. It is tempting to introduce a constraint by analogy of something akin to the second principle of thermodynamics, stating *grosso modo* that any physical system strives after reaching a maximum level of chaos, or entropy. In resource terms, such a constraint would impose a (not necessarily precisely quantified) limit. It is well known that oceans are in a state of maximum entropy. Hence, relatively small amounts of chemical elements diluted in oceans are barely accessible for mankind, and have therefore no intrinsic value, or even meaning, as a natural resource. By analogy, we assume that a chemical element that is infinitely diluted in the Earth's crust could not be of any direct use to humanity. Thus, a finite norm can be defined, determined by the level of dilution by which it is available on Earth.

Phosphorus is found in the Earth's crust at different concentrations, the highest found at the famous 'geological scandals' of Morocco and at the Kola Peninsula.[14] Deposits where phosphorus is abnormally concentrated, like at these sites, are exploited first. Commercial phosphates contain 55 to 70% of tricalcic phosphate. To pretend that we would be able to move forever down the concentration curve is similar to pretending that it would be profitable to exploit the infinitely diluted elements in oceans.[15] As the concentration decreases, the energy required to extract a given chemical element increases.[16] Theoretically, one should employ an infinite amount of energy to extract an element whose concentration is nearing zero. We therefore introduce, at the level of passage A, a constraint that we shall call the *absolute* (or *finite*) *threshold*, which is equal to the level at which all available energy is used to extract the desired resource. Even if we suppose that all available energy at any moment is used for the sole purpose of extracting an element from nature, a finite threshold exists to the quantities we can obtain. Two remarks can be made at this point:

I. The existence of a finite threshold implies an absolute norm, if no further qualification is placed on the way the objective 'avoiding exhaustion' is formulated. One cannot avoid the exhaustion of a natural resource, if dilution is taken into account.
II. We have taken phosphorus as example, but the reasoning is, of course, valid for all elements. Thus an economic problem exists regarding the allocation of total energy.

These two observations lead us to answer negatively the question: Is it possible to establish a norm independently from any economic optimisation? This would be enough to reject the two-step approach. Let us suppose, however, that somehow a norm *has* been established, for every element.

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[13] The origin of this scarcity can be found in the need to use mineral fertilisers only, instead of either mineral or vegetal ones.

[14] If we except the deposits of Nauru, Christmas Island, etc., which are very rich (in some cases over 90 per cent of tricalcic phosphate) but are nearing exhaustion.

[15] We are not talking here about polymetallic nodules, but about chemical elements which are completely dissolved in sea water.

[16] Here the concept of *scarcity* takes on its full meaning: "If the entropic process were not irrevocable (...) scarcity would hardly exist" ([10], p. 6). Accordingly, it is because more energy, *ceteris paribus*, is required to obtain the element from lower concentrations that the element is scarce.

This brings us to a fundamental point: phosphorus is rigorously non-substitutable. There is neither substitute nor replacement for its use in fertilisation. Phosphorus is active in all reactions that take place in plants. The reason for this appears clearly vis-à-vis its role in vegetation growth at the molecular level. The three main elements that are indispensable for the growth of plants, with each their specific roles (nitrogen, potassium and phosphorus), are indispensable and non-substitutable.

Because of the non-substitutability of phosphorus, some tenets of traditional economic analysis become irrelevant: "Orthodox economic theory has assumed that all scarcity is relative. (...) Therefore the answer to scarcity is always substitution. (...) But price rigging by itself is ineffective in coping with increasing absolute scarcity, since its mode of operation is only to induce substitution."[17] This example of orthodoxy is not a thing of the past. The Brundtland report tacitly assumes that every mineral raw material will, sooner or later, acquire a substitute. "With minerals and fossil fuels, the rate of depletion and the emphasis on recycling and economy of use should be calibrated to ensure that the resource does not run out before acceptable substitutes are available."[18] In any such or similar frame of thought, that is, if in the end substitutability is to prevail, any reasoning in terms of the existence of an energetic norm loses its relevance. It then seems preferable to define a set of norms. For instance, one could determine which elements are necessary to humanity's survival, and which not, and subsequently adopt the most rigorous norm for each of the necessary ones.

How now can we define sustainability for phosphorus? We could introduce a concept of 'geological reproducibility,' in analogy to 'solar transformity' thus defined: "Consequently with the solar transformity of any natural resource, the time necessary for reconstituting one joule of this resource may be determined. According to the actual quantity consumed in period *t*, the time required to reconstitute the amount consumed can be obtained by multiplying the reconstitution time per unit determined above."[19] We could thus try to compute the time needed to reconstitute today's phosphorus reserves. However, the entire preceding discussion prompts us to ask: At what concentration? We have seen that, were this question not addressed, the time required could be of any length, even zero. If a figure is given for the concentration level envisaged, one can actually calculate this time. One should then realise that three phosphorus cycles can be distinguished.[20]

1. A *long cycle* (with an order of magnitude of a billion years). This cycle starts with igneous rocks that undergo alterations.[21] Many different transformations (that may include interference with living beings) lead to a precipitation in sediments. The latter, as a result of tectonics, are incorporated in superficial magma layers or in metamorphic rocks.
2. A *medium cycle* (thousands to millions of years). This cycle is a kind of loop inside the first one. It relates to phosphorus in solution and begins with either igneous rocks or sediments. Through plants and animals, biochemical processes make phosphorus accumulate as organic deposits (of e.g., the guano type) or as mineral deposits (e.g., sedimentary phosphate).
3. A *short cycle* (typically a few years). This cycle starts with the up-take and absorption of phosphorus from soil to vegetation. From plants, it is subsequently transferred to animals, as a result of the latter nourishing themselves with the former, as well as through animals and humans feeding themselves with other animals. From animals it is returned to soil.

Cycles 1 and 2 require geologic or close-to-geologic time lapses. Even if we suppose that the processes that underpin them are active today, in human terms both of these cycles are immobile. Therefore, we can establish sustainability only by reference to cycle 3. It is cycle 3 that made agriculture possible since Neolithic times. Cycle 3 can be considered as a natural recycling. It is not closed, however, since leakage occurs at every round. This is, of course, a rather general phenomenon.[22] A proportion of the phosphorus gets dissolved, finds its way to rivers and is carried away to the ocean. Another proportion gets too diluted in soil, so that plants cannot absorb it. Liebig had already observed that manure and plant waste give back to the soil less nutritive elements than the harvest takes out.[23] We therefore need a complementary fertilisation, outside the cycle. If one stays inside cycle 3, soils become useless after a few centuries.[24] For thousands of years it has been possible to start a new cycle on virgin lands, whenever necessary. In doing so, mankind could escape important resource constraints. This phenomenon has been dubbed *cowboy economy*[25] or

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[17] Daly ([19], p. 17).

[18] *op. cit.,* p. 46.

[19] Faucheux ([14], p. 6).

[20] Cf. Hénin [20].

[21] The deposits of phosphate are either *sedimentary* (most of them), or *igneous* (mainly the Kola deposit).

[22] See, for example, Solow [21]: "This is true even of recyclable materials; the laws of thermodynamics and life guarantee that we will never recover a whole pound of secondary copper from a pound of primary copper in use, or a whole pound of tertiary copper from a pound of secondary copper in use. There is leakage at every round." ([21], p.2).

[23] In this connection, one can read in the Brundtland Report, p.135: "(...) our generation lives (...) at the expense of the coming generations, thoughtlessly drawing on the basic reserves of soil fertility accumulated in the millennia of the biospheric development, instead of living off the current annual increment." But in fact that yearly increment is *negative* if we make the calculations at the level of the chemical element.

[24] This is the true meaning of the expression "le blé qui dévore la terre" (translation: "the corn that devours the earth") ([22], p. 18).

[25] Boulding, quoted in Krabbe et Heijman ([23], p. 6) and Nordhaus ([24], p. 22).

frontier economy[26]. However, the Earth is finite, so that there are obvious limits to reckless flights into the future. In the near future, only 40% of the necessary increments of agricultural production could come from exploiting virgin lands. The remaining 60% must be of the Green Revolution type, meaning that it will require the use of mineral fertilisers, originating from outside cycle 3.[27] Cycle 3 involves – in the economic sense of the word – a sort of *ratchet effect*.[28] Humanity has been able to free itself from cycle 3, partly because it started exploiting mineral deposits of phosphate. This enabled world population to reach its present level. From this level, it cannot decrease significantly in the short or medium term. A mechanism has been put into work leading to such conditions that prevent a swift return to the original cycle 3, and thus to true sustainability.

CONCLUSION

In this paper, we defined some basic concepts used extensively in environmental sciences: *nature*, *natural resources*, *reserves* and *raw material*. We also defined the way in which they interact with one another. These definitions were then illustrated in three different examples, mainly related to three different disciplines: physics, biology and chemistry. Meanwhile, these concepts were used to show how other essential concepts such as *renewability* and *sustainability* can be obscured by the lack of proper definitions of the former. It appeared that making appropriate definitions of a variety of fundamental concepts can avoid lots of confusion in environmental sciences, especially in cases where social and natural sciences meet, and where scientists from these different fields need to communicate with each other.

In this article we define *nature* as the collection of conditions imposed on mankind that precede all human needs and activity. Human needs are the basic wants of mankind, which are to a large extent socially and economically determined. The existence of human needs creates *natural resources* from natural conditions. *Reserves* come into being by a whole range of factors, mainly economic but also technical, political and strategic, which intervene and delimit the share of resources that at any given time can effectively be exploited. *Raw materials* are produced from natural reserves as a result of committed and pro-active human activity. The availability in the Earth's crust of oil resources constitutes a good example to elucidate these definitions.

The first case of nuclear energy demonstrates the extent to which the kind of resource definition employed can result in fission fuel availability varying over several orders of magnitude. It is apparent that our proposed definitions can take away practically all confusion vis-à-vis the nuclear energy resources available on Earth, and it is shown how reserves can evolve under the influence of a variety of economic and technological developments. With our definitions, we see that essentially no difference exists, in our second case, between non-renewable resources such as fossil fuels and the specific example of human land use resources, and that especially regarding this subject matter social and natural scientists can easily run into conflict, merely as a result of concept confusion. A solution is to undo concepts like non-renewability and non-reproducibility as much as possible of their economic content. The difficulty hereof is shown in our third case, in which our definitions shed light on how the meaning of concepts like concentration, dilution and energy use is determinant for the existence of renewability and exhaustion of an essential natural resource like phosphate. This case emphasises what is gradually becoming increasingly clear: the challenge for mankind to establish – or return to – true sustainability is sizeable.

As an overall conclusion, and as a recommendation for future work, we advocate that for a wide set of fundamental terminology further efforts are undertaken to design definitions that are employable in all different disciplinary approaches used in environmental sciences. Such efforts will be especially worthwhile in the light of the often encountered experience that confusion is already created among scientists within one single discipline, as a result of unspecified or imprecise usage of particular reserved wording.[29] Only via generally agreed and precise definitions of common concepts genuine multidisciplinarity can be achieved, especially when the environment is concerned. In this paper, we have provided a number of such definitions, but many others still need to be provided. For example, two paramount concepts that still ought to be extensively researched in this sense are 'energy' and 'entropy,' the discussion of which scientists Georgescu-Roegen and Daly have already importantly contributed to. Not only do we recommend the future use of the definitions provided above, or similar definitions, in environmental sciences, by a scientific community as large as possible. We also recommend, in addition, that the rigour in making definitions as we have attempted to put in practice here, is equally employed vis-à-vis remaining confusing environmental terminology.

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[26] Howe ([25], p. 62).

[27] Lavers [26].

[28] In physics (in particular, electromagnetism) its approximate analogy is referred to as *hysteresis*.

[29] This confusion is subsequently amplified when these scientists communicate with scientists from other fields. An appropriate example in case is the imprecise use by economists of the concepts 'equilibrium,' 'optimal' and '(ir)reversible,' which all three can be employed in various different meanings.

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