Gaia, our new common.

Some preliminary questions on earth system science and common-pool resources theory in the study of global human/environment relationships.

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"Our planet is one of exquisite beauty: it is made of the breath, the blood, and the bones of our ancestors. We need to recall our ancient sense of the Earth as an organism and revere it again. Gaia has been the guardian of life for all of its existence; and we reject her care at our peril" (James Lovelock, 2000, 418).

Introduction

It is unusual to introduce a paper using a chart. Nevertheless, Tyler Volk - Earth biology professor at the New York University - proposed the picture showing the increase of atmospheric carbon dioxide (CO_2) in the last forty-five years in Mauna Loa, Hawaii (see figure 1) as "candidate for the all-time list of famous graphs" (Volk, 1998, 6). Considering that CO_2 is the most relevant between greenhouse gases and that geological long time series show its high correlation with global average temperature (Schlesinger, 1997, 10), the candidate will probably win the prize. According with data collected by analyzing air bubbles preserved by glacial ice, since no direct measurements existed before 1958, the CO_2 concentration in the centuries before the industrial age was roughly stable around 280 parts per million (ppm) (Etheridge *et al.*, 1998; Schlesinger, 1997, 370-371; Volk, 1998, 7). Comparing it with the present value of 373 ppm we note a rising close to 100 ppm in two centuries, half of which occurred in the last 35 years[1]. The increase is of the same magnitude as the one that occurred at the end of the last glacial epoch, but it has taken place at an extremely faster rate (centuries instead of millennia) and "[has carried] the planet into a range of concentrations

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[1] Data source: Scripps Institution of Oceanography (SIO), University of California, 2003.

never before experienced during the evolution of modern human social and economic systems" (Schlesinger, 1997, 10).

There are no scientific doubts that anthropic activities - first of all the burning of fossil fuels - represent a key cause behind this impressive, global scale process. Though more uncertainty regards the consequences that the related increase of average temperature will have on human and other living beings, still a reasonable worry is growing (IPCC, 2001). Ecologists and natural scientists often wonder why "irrational" human beings seriously risk to undermine their own future by undertaking activities that are clearly unsustainable at the global level. However, the answer is easy for most social scientists: that is just a large scale version of a collective action problem. Its most famous representation is probably Garrett Hardin's "Tragedy of the commons" model, which leads to the prediction of common resource destruction (Hardin 1968). While Hardin's scheme appeared too pessimistic and has been contradicted by empirical evidence at the local level (Ostrom 1990), it unfortunately looks more fitting with many recent findings on a global scale, including climate change problems. This leads to a wide set of intriguing issues both from the social and the natural science point of view. They embrace topics like the following: the question of why only after the industrial revolution, after millennia of active interventions on ecological systems, human beings have altered global long lasting equilibria; the conceptual problem of the differences between local and global resources, including the issue of the application to the global level of common-pool resources (CPRs) theory findings at the local one; and the question of global externalities of action, which are not limited to anthropic activities but linked globally all beings living on Earth.

The present paper - which is a preliminary output of a long process of interdisciplinary work among physicists, natural and social scientists - tries to address some of the above questions. Its main argument is that the anthropocentric and institutional view of CPRs theory, although appropriate for the analysis of local resources, suffers from significant shortcomings when applied to global commons. Without discussing the foundations of CPRs theory, we suggest the introduction of some basic elements of Gaia theory - which considers Earth (Gaia) as a complex self-regulating system producing a number of emerging properties like, for instance, climate and atmospheric chemistry regulation - alongside with the "traditional" institutional analysis tools of CPRs research, as a way to reach a better understanding of issues regarding global commons. While we recognize that CPRs theory offers fundamental insights in a context where neither external authority management nor privatization of the resource is possible, following James Lovelock (1988, xvii) we also note that "Gaia theory forces a planetary perspective" and represents a major drive for the abandoning of purely anthropocentric paradigms and for the development of new analytic and conceptual tools able to cope with topics like large-scale resources, global changes and a world of overwhelming complexity.

The paper is organized by questions. The first one, "What is Gaia?", a name drawn from a chapter in Lovelock's book "The ages of Gaia" (1988), introduces some of the main findings of Gaia theory. The second one deals with the problem of linking Gaia and the institutional analysis of global commons done by CPRs theory. The third examines similarities and differences between local and global commons. The last one asks why what used to be a global public good became a global common (Gaia) after the industrial revolution. Those are, indeed, just a few of the problems which emerge when trying to draw together two wholly different scientific fields. Many other related questions could also present, at least, as much interest as the ones discussed here, but the aim of the paper is more to offer some insight for new research than to give firm answers to the queries we pose. Moreover, in order to avoid an excessive long and complex essay, the basic of CPRs theory will not be presented and assumed as known by the reader. Those who wish to learn more on the subject can see Ostrom (1990) and Ostrom *et al.* (1994). Italian readers can also find a short introduction to it in Bravo (2001).

What is Gaia?

Gea (Gaia) in the ancient Greek mythology was the spouse of Uranus, first lord of the cosmos, mother of everything and grandmother of Zeus (Scarpi, 1996, 8-9). It is not surprising that James Lovelock found her name appropriate[2] for his vision of Earth as a global physiological system, a super-organism able to self-sustain and self regulate over the eons[3]. Gaia is a metaphor and does not entail the idea of a giant volitional being. Still, amazing properties emerge when considering life, soils, oceans and the atmosphere as an interacting system at the planetary level (Volk, 1998, viii-ix). First introduced at the beginning of the '70s, the Gaia hypothesis argues that the chemical composition of the atmosphere, the oceans and the Earth crust, along with the climate, are regulated at a comfortable state for life as the result of the behavior of living organisms (Lovelock, 1972 and 1979). This implies both that living organisms are active participants of the planet evolution, including the evolution of its physical components (the *matrixes*, in Gaia theory terms), and that the evolution of species is strictly coupled with the one of the environment where they live (Lovelock, 1988, 19-35). What is most surprising in Lovelock's model is the capacity of the biota to regulate the atmospheric chemistry and to stabilize the climate over time. In absence of life, the atmospheric

[2] The name was suggested to Lovelock by his friend, the Nobel prize novelist William Golding.
[3] An *eon* represents, in Lovelock's (1988, 65) terms, 10^9 (a billion) years.

composition of Earth would probably be not so different from the one of its neighboring planets, Mars and Venus: a proportional overwhelming abundance of carbon dioxide, with little nitrogen and only traces of oxygen (see table 1). At the beginning of its existence, 4.5 billion years ago, Earth atmosphere was also rich in CO_2 and deprived of oxygen. Fortunately (from our point of view), the development, about 3.5 billion years ago, of photosynthetic organisms able to use solar energy to convert CO_2 and water in useful carbohydrates while releasing oxygen as waste at the same time[4], changed the atmosphere in something that the members of the respirers guild[5], including the newcomer humans, can breathe. The decline of atmospheric CO_2 (a well known greenhouse gas) as the result of biotic-enhanced burial of carbon in the Earth crust minerals has contributed to the reduction and to the stabilization of Earth mean temperature, despite the fact that solar radiation has increased some 30% in the meantime (Lovelock, 1988; Schlesinger, 1997; Volk, 1998).

The effects of life on climate are much more complex than the short picture above, but it is worth noting that the average mean temperature has been kept in a narrow range, just the right one for life, during the whole evolution of biosphere, i.e. some 3.8 billion years. That could appear an excessively peaceful picture, given all the changes that have occurred since the Archean, including variations in atmospheric composition, impacts of large meteorites, mass extinctions, etc. Nevertheless, Earth temperature never overcame the narrow limits where life is possible (Lovelock, 1988, 150-151; Volk, 1998, 234-239). That could be rather surprising, but the systemic view of Gaia theory can help our understanding: "[…] things that seem obscure within their separate fields of science become clear when seen as phenomena on a living planet. Gaia theory predicts that the climate and chemical composition of the Earth are kept in homeostasis for long periods until some internal contradiction or external force causes a jump to a new stable state." (Lovelock, 1988, 13).

It is not possible to offer here even an approximate sketch both of Gaia theory - which developed in a new scientific field, known as Earth system science or geophysiology - and of Earth history from the point of view of Gaia[6]. It is instead important to note that, in order to explain (at least partially) all the wonderful capabilities of Gaia, we do not need the assumption of a purposeful self-regulating planet. The risk of teleological explanations is actually one of the main criticisms advanced against the theory[7]. In order to reply to its critics, Lovelock developed a simple simulation model, named Daisyworld, showing that global scale climate regulation can result as emergent property of biophysical systems without the need of any volitional planetary control mechanism (Watson and

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[4] The basic photosynthetic reaction is $H_2O + CO_2$ (+ sunlight) → $CH_2O + O_2$.

[5] A *guild*, in geophysiology, is formed by all organisms carrying on the same biochemical function.

[6] See the excellent Tyler Volk's (1998) book for more details on Gaia theory and Gaia history.

[7] For further information on the criticisms advanced on Gaia theory, see Kirchner's (1989) article and the book edited by Schneider and Boston (1991).

Lovelock, 1983). Daisyworld is an imaginary Earth-like planet where the only plant species are daisies, some light and some dark colored. The planet is well watered by night rains and all days are cloudless. Greenhouse effects are voluntarily not included in the model in order to keep it simple (the CO_2 in the atmosphere is assumed to be constant), hence the planet average temperature is a function of solar illumination and of the planetary albedo[8] only. Dark and light daisies possess different albedos, respectively under and above the bare ground one, and have therefore the possibility to change local temperature by absorbing or reflecting more sunlight than would happen in their absence. If daisies are sufficiently spread across the planet they can also significantly modify the average planetary albedo, affecting therefore the temperature of the whole planet.

In the basic Daisyworld model, the only external changing variable is the solar output, which - as with our Sun - steadily increases over time and therefore affects linearly the planet temperature. At first, the planet is too cold for the daisies - which need a temperature between 5° and 40°C, with a best at 20° - to grow, but, when the temperature reaches 5°, daisies start spreading over the land. First, dark daisies - which absorb more of the sunlight and increase the temperature of the areas where they live - are favorite, but, as time passes and solar radiation increases, the capacity of light daisies to reflect more of the radiation becomes increasingly a competitive factor and they gradually replace the dark ones over most of the planet. At the end of Daisyworld time, the Sun becomes to hot for life and leads to the extinction of daisies all over the planet (see figure 2a).

The emerging property of the model is its capacity to stabilize the planet temperature. Figure 2b shows the average temperature of Daisyworld in comparison with that of the same planet in absence of daisies: surprisingly, the mean temperature of Daisyworld is roughly constant at a value close to optimal for the growth of daisies, whereas the temperature for the "dead planet" increases linearly over time. Moreover, this equilibrium is long lasting and persists as long as life is present on the planet. Only when the solar output increase exceeds the system limits - i.e. despite the fact that light daisies entirely cover the land the temperature rises above 40°C - its crash leads rapidly to the extinction of all daisies and to the return to the abiotic state of constant temperature raise. Lovelock (1988, 42-64) demonstrates that those findings are robust when the basic parameters of the model are changed and when the effects of plagues, of more species of daisies and of other living beings (like rabbits and foxes) are included.

Daisyworld is just a simulation model, but offers important insights of how the different parts - biotic and abiotic - of the system-Earth could be linked and suggests the need of more research in this direction. Describing it, we tried to give a simple sketch of the "Gaian" point of view over what

[8] i.e. the quota of light reflected back to space, which is 0 for a perfect dark body and 1 for a perfect white one

social sciences usually consider "natural resources" or, simply, "environment". How to include it in our CPRs management analyses is the matter of the next question.

How can Gaia theory help the research on global commons?

Even if Hardin's (1968) concerns in creating "the tragedy of the commons" model were mainly linked to the consequences of world overpopulation, the majority of subsequent researches on CPRs - including Ostrom's (1990) influential book "Governing the Commons" - enquired local issues only (Dietz *et al.*, 2002). Most of the theoretical work on large scale resources started only in the middle nineties (Gibson *et al.*, 1998; Keohane and Ostrom, 1995; McGinnis and Ostrom, 1996) as direct extension of local commons research. This led to emphasize the common aspects of the different levels of analysis, as McGinnis and Ostrom (1996, 469) did arguing that "the lessons learned from past research on micro CPRs has substantial applicability to the problem of dealing with patterns of international cooperation and conflict". Reasons supporting their view included: "(1) The analytical structure of some global problems shares similar features with the analytical structure of many local CPRs. (2) Starting with theories and models devised for the analysis of local CPRs may speed the work in developing theories and models at the global level. (3) Many global problems […] are themselves the result of inadequate solutions at a microlevel of a complementary and interactive commons problem" (McGinnis and Ostrom, 1996, 469-470).

Following those arguments, theoretical models developed for local resources were also used for the analysis of global commons management institutions, e.g. the Montreal protocol on chlorofluorocarbons (CFCs) and the Kyoto protocol on CO_2 emissions (Gardner *et al.*, 2000). While giving important insights, this approach misses the fact that CFCs, known for their destructive capacity of stratospheric ozone, are also greenhouse gases (like other atmospheric trace gases, e.g. methane and nitrous oxide) and that climate changes are not driven solely by anthropic CO_2 emissions (Elzen and Schaffer, 2002; Lovelock, 1988, 169-170; Schlesinger, 1997, 72-74). Therefore, while acting for CFCs control, the Montreal protocol (with its London 1990 revision) displays also some influence on global warming[9] and, probably, on the balance of the global cycles of other elements. This challenges the standard social sciences and policy models representing the environment as formed by different independent resources, separately exploited by human users. From the point of view of Gaia theory, we have just one "resource": Gaia (also known as Earth, the Ecosphere, etc.). Gaia has been in homeostatic equilibrium for long periods of time, but human

[9] Influence mitigated by the fact that, unfortunately, some of the CFC substitutes are also greenhouse gases.

beings can perturb it with their actions in the short time[10]. Biogeochemistry and geophysiology tell us that all planetary elements are moving through the biosphere and the physical matrixes of Gaia - the atmosphere, the oceans and the Earth crust - in global cycles and that the cycles of different elements are not independent. For instance, the global carbon cycle is strictly connected with the oxygen one; moreover, carbon forms important compounds with elements such as hydrogen and nitrogen (Schlesinger, 1997, 358-382). Therefore, considering different "resources" as separate and viewing human beings as external to the resources they use can lead to serious mistakes both in our analysis and in our predictions. Reductionism can help in reaching better models but exposes us to the risk of losing the basic idea of the complex interconnections among the different parts of the planet.

On the other side, Gaia theory "provokes" a view of the Earth where: (1) life is a planetary-scale phenomenon; (2) the functions of any single element in Gaia are not separable from the functions of all other elements; (3) the evolution of organisms and the evolution of the physical and chemical environment where they live are strictly coupled as a single, indivisible process; (4) some elements can play a "keystone" role in the global cycles of matter and causes (Lovelock, 1988; Volk, 1998). From this point of view, the global resources are no longer passive sinks for human emissions, relatively independent and endowed with fairly constant regeneration rates. The role of natural systems is anything but passive. Our global resources are "natural services" offered by Gaia, services that include, among others: the capture of solar energy and its transformation in chemical energy that animals can use; the regulation of atmosphere composition and of the climate; the decomposition and the recycling of organic wastes; or the regulation of the water cycle (Costanza *et al.*, 1998; Daily, 1997). These services are not given independently: photosynthesis is a step of the carbon cycle, which influences the climate, the water cycle, the recycling or organic compounds and many other aspects of the system Earth. Moreover, not all the uses of the same natural service are equivalent from the point of view of geophysiology. To acquire energy eating (or maybe even burning) biomass and subsequently expiring part of the carbon as CO_2 cannot alter the global carbon equilibrium, it is actually a necessary part of it. Conversely, to emit CO_2 as the result of the burning of fossil fuels links us to buried carbon, which naturally would be returned to the atmosphere only in millions (or hundreds of millions) of years, and can alter the equilibrium in a short time (see below).

Gaia theory helps to understand what are the resources we really use and how we use them. Given its predictive power, it offers the capacity to distinguish between public goods and common-pool

[10] As aerobes, humans are by rights members of the respirers guild. Nevertheless, using their technology they also perform a number of other different chemical transformations and can hence be considered as a specific guild by themselves (Volk, 1998, 248-250).

resources on the global scale. Theoretically, it is clear that in a thermodynamically closed system like Earth, where all elements need to be recycled, nothing except solar illumination, which is a free gift coming from outside, could be a pure public good since subtractability is always above zero[11]. From this point of view, Gaia is the common of all commons and its users are all the components of the biosphere, from bacteria to human beings. Nevertheless, it is both analytically and practically of extreme importance to discern resources where rivalry is negligible from the "scarce" ones (Keohane and Ostrom, 1995, 13-15). Watching Earth using the lenses of Gaia theory helps to do it, i.e. to understand the consequences of human action on global natural equilibria before the alterations become matter of serious concerns. Gaia theory has, therefore, not only academic interests, but also shows important applications for the planning of preventive and not just of *ex post*, harm-reduction, environmental policies.

What changes moving from local to global CPRs?

Studies of local and global CPRs can show important similarities, but significant differences also arise when moving across different levels of analysis. The problem of scale is manifold and regards physical, social and institutional dimensions. CPRs theory mainly focuses on the last one, studying similarities and differences between local commons and international resource regimes, addressing problems like the effects of the augmentation in number and in heterogeneity of the users on resource-governing institutions (Keohane and Ostrom 1995; McGinnis and Ostrom, 1996). The actors' definition changes when moving from local to global scale, with collective actors - states, national and multinational corporations, NGOs, international governmental organizations[12] - replacing the individuals - farmers, fishers, etc. - in the institutional building process. Individuals (along with collective actors), however, maintain a relevance as resource users, creating a picture where a multitude of micro actions aggregate to result in global outcomes. On the other side, it looks unlikely that the community, an important social force influencing the institutional performances of local commons management (Bravo, 2002; Singleton and Taylor, 1992), will maintain a significant role on the global level (Young, 1995, 31-33). Nevertheless, the effect of social factors influencing the spreading of information and the formation of collective consensus regarding the relevance of specific topics (e.g. the "ozone hole", or the "global warming") remains

[11] John Dales (1968) proposes also gravity as an example of pure public good.
[12] See McGinnis and Ostrom (1996) for a typology of actors involved in the international regimes definition.

non negligible. The so called "epistemic community"[13] can hence play an important role in setting the political agenda and in forming the "commons understanding" that can provide the basis for international agreements and cooperation (McGinnis and Ostrom, 1996, 472).

Moving from local to global, changes do not only concern social and institutional dimensions. Gaia theory indicates also some major differences related with the shift from thermodynamically open to thermodynamically closed systems and the closing of all matter cycles. Animals and plants are thermodynamically open systems, which means that they exchange matter and energy with the surrounding environment. By so doing they continuously reduce internal entropy at the expense of an increase of universal entropy and the process stops only with death (Lovelock, 1988, 25-26). In the same way as the living organisms they encompass, local ecosystems are open. Their boundaries can be drawn analytically by comparing fluxes of matter and energy inside the systems with those connecting them with the external environment and observing that it is possible to understand some properties of the systems by considering the local dimension only. For instance, plants in a forest produce biomass, which is consumed by animals. In turn, animal excretions, transformed by soil bacteria, return fundamental nutrients to plants, closing the circle and permitting to maintain the system over time. Nevertheless, its boundaries do not comprise fluxes of matter and energy which are fundamental for its life, including solar energy, CO_2, and oxygen. Ecosystems exchange matter and energy through their permeable boundaries in a network that embraces the entire planet, which is the only level where all matter cycles close. This leads to a fundamental difference between any local system and the global level. While the first ones are thermodynamically open systems the latter is a thermodynamically closed one, i.e. a system which exchanges energy but not matter with the outside[14].

The distinction between many open local systems and a single closed global system encompassing all the local ones leads to two important considerations. First, on the global level any long term sustainability is impossible without recycling all elements. This means that the output of someone must always be the input of someone else: "the pollution of one is the meat of another" (Lovelock, 1988, 26). The only real input from the external is that part of solar energy - around 0.1% of the total radiation reaching Earth (Volk, 1998, 158-166) - captured by photosynthesis: surprisingly small but essential for all the planet life. Global common students, unlike local resource ones, therefore need to take the closure of the system into account. Neither those institutions that do not

[13] It is worth noting that the global "epistemic community" reveals some common aspects with the traditional communities: a common background of knowledge and, at least partially, values; a relative stability of its members; and frequent relations between them, both face to face and ICT mediated.

[14] This is an approximation, since Earth exchanges indeed some matter with the outside, e.g. because of meteors or by the losing of light elements, like hydrogen. Still, those exchanges are negligible if compared with the total mass of the planet.

create incentives in the direction of recycling the elements nor individual behaviors able to produce local sustainable equilibria by displacing environmental costs can enhance sustainability. This is another point arising from the thermodynamic relation between local and global systems: since local ecosystems are open, it is possible to reach local long term equilibria by increasing global unsustainability. A classical example of open ecosystem exploitation is the rich agriculture of ancient Egypt, where the annual flood of the river Nile granted the crops with a reliable flow of nutrients in the form of slime, mostly coming from the uplands of Ethiopia and Uganda. This permitted to maintain a dense population for millennia and to create one of the most complex civilization of the past (Ponting, 1992; Smil, 1994). In the present time, the great development of international trade has immensely increased the possibilities of achieving local environmental equilibria at the expense of global sustainability (Andersson and Lindroth, 2001; Bagliani and Bravo, 2003). By importing and exporting goods, whose production implies the use of both renewable and not renewable resources and of energy, trade links not only different economies but also different ecosystems. Moreover, since market prices do not usually include environmental costs - which are not part of the production factors, but come as free natural services - the import of sustainability is free: i.e. a positive externality (for buyers) offered by the work of producers that internalize most of the environmental costs. For instance, a country like Switzerland, well known for preserving high environmental standards in its territory, cannot represent a model of sustainable development if we consider its impact on a global scale. In order to better understand this point it is practical to use a synthetic indicator like the ecological footprint. First introduced by Wackernagel and Rees (1996), the ecological footprint represents an assessment of the total amount of natural capital consumption done by calculating the total area needed to uphold all the consumptions of a given population in a sustainable way [15]. Comparing the *per capita* average ecological footprint of Switzerland with the productive capacity of the country, it is possible to see that each of its inhabitants consumes yearly 2.3 hectares of average productivity more than what its territory can produce. Since the environment is not degrading (i.e. it presents a local equilibrium), the maintaining over time of high consumption levels is reached not by reducing local natural capital, but by importing sustainability from the outside. Switzerland is not the only consumer of foreign natural capital, and by no way the stronger one (see table 2). However, since Earth approximates a closed system, no better position in global sustainability can be obtained achieving local sustainability by way of movements (trade) inside the system. This must alert the researchers on local CPRs management: without considering the global (Gaian) level it is possible to evaluate as

[15] For more information on the ecological footprint and on its use, see Wackernagel and Rees (1996). A special issue of Ecological Economics (vol. 32, n. 2, 2000) has also been dedicated to the concept.

positive (i.e. sustainable) the effects of institutions that actually foster unsustainability on a wider scale. To bear in mind that Earth is a system of closely coupled cycles of elements can help to avoid this risk.

Why did Gaia turn out to be a global common?

Although the history of the destructive action of human beings on the environment looks long and harsh, before present damages were limited only to the local scale (Broswimmer, 2002; Ponting, 1992). Conversely, the research on CPRs management has told us that many communities have also been able to sustainably govern their own resources - woods, pastures, fisheries, water basins, etc. - without depleting them. In both success and failure cases, the resources were local or, less frequently, regional, while the natural services of Gaia, including atmosphere chemistry and climate regulation, remained unaltered over the millennia: public goods that turned out to global commons only after the industrial revolution. The difference between public goods and CPRs is a matter of subtractability, also known as consumption rivalry (Ostrom *et al.*, 1994, 6-7). The problem is why natural cycles, that were in long-time equilibrium, suddenly[16] lost their stability becoming, from an anthropocentric point of view, subtractable resources. For instance, the atmospheric CO_2 concentration in the last 220.000 years has varied slowly between 200 and 280 ppm and has been stable around 280 ppm since the end of the last glacial epoch, some 17.000 years ago. Suddenly, at the beginning of the XIX century, it started to rise, reaching the present level of 373 ppm in less than 200 years[17] (see figure 3) (Etheridge *et al.*, 1998; Schlesinger, 1997, 367-371). In pre-industrial era the equilibrium was homeostatic because of the dynamic stability of a cycle that included, among others, plant and bacterial photosynthesis, consuming CO_2, and both animal respiration and anthropic CO_2 production by burning organic non-fossil fuels (wood, charcoal, excrements, etc.). It is worth noting that in this long period the total human population rose from a few millions during the Paleolithic to a billion at the very beginning of the XIX century, suggesting that the shift of natural services from global public goods to global commons is not (or not only) a quantitative matter of growing human population. The qualitative difference is, of course, the industrial revolution, which, from an energetic point of view, is characterized by the burning of fossil fuels. However, the burning of fossil fuels releases CO_2 just like wood, charcoal or horses. So, why did the rise in CO_2 atmospheric concentration start only when coal (and then oil) replaced organic fuels, water, wind and animate energy in the production process? Moreover, the estimated release in the

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[16] The changes has occurred indeed at an incredibly fast rate considering Gaia time scale.
[17] Similar trends are also visible for nitrous oxide, methane and sulfate aerosols (IPCC, 2001).

atmosphere of carbon from fossil fuels was about 6 × 10^{15} g/year at the beginning of the 1990s, much lower than other natural sources like, for instance, plant and animal respiration that release approximately 120 × 10^{15} gC/year (Schlesinger, 1997, 358-361). A related question is, therefore, how can a minor flux alter long lasting climate equilibria?

A geophysiological view can (again) help to recompose the puzzle. From this point of view, not all carbon atoms are equal. A carbon atom has a mean residence time of about 9 years in land biomass, with large variations depending on plant types and tissues. Conversely, each carbon dioxide molecule in the atmosphere has the potential to be captured by vegetation in approximately 12.5 years (Schlesinger, 1997, 142-143 and 360). By burning wood or other organic compounds, humans release carbon at a rate comparable with the natural cycles of plant and animal respiration, photosynthesis, and exchanges with the oceans. Those emissions can therefore be compensated by Gaia homeostatic capacities, as shown, for instance, by the stability of atmospheric CO_2 concentration even in presence of the massive deforestations that took place during human history, for example in the Mediterranean basin in classical times and in continental Europe in the centuries before the industrial revolution (Ponting, 1992). On the other side, fossil fuels link human action to a very different pool of carbon, with very small annual variations and whose cycle no longer develops at human but at geological time scale. The geochemical carbon cycle shows indeed limited natural exchanges with the biogeochemical one, around 0.1 × 10^{15} g C/year (Schlesinger, 1997, 359). Human beings, by burning fossil fuels, create a link between those two systems, changing the natural geological pace of the first one and causing strong short term alterations of the second one, notwithstanding the long term homeostatic properties of Gaia. This happens because the two subsystems, now connected by human activities, are in natural equilibrium on very different time scales: the first one in geological time scale, 10^6-10^8 years, and the second one in living beings time scale, 10^1-10^2 years. Compare, for instance, the 400 millions years or more that a carbon atom would spend if sequestrated in marine carbonate with the mean residence time of 9 years in land biomass (Schlesinger, 1997, 142 and 368). In this setting, the artificial pumping of carbon from the geological reservoirs to the atmosphere, although small in absolute terms, creates an unprecedented tunnel between the two subsystems, bypassing at the same time the self-regulation capacities of Gaia. It is likely that in the long term that modest, after all, alteration of biogeochemical cycles will be no more than a blink of an eye in the eons of Gaia's life. Nevertheless, it may cause severe adverse effects in the short term (our 10^1-10^2 years time scale) where we must expect temperature increase, precipitation rate changes, rise of sea levels, etc. (IPCC, 2001).

Moreover, the global carbon cycle is just one of the strictly interconnected element cycles of Gaia "physiology". Human beings are altering most of them with global and local consequences that are difficult to predict. What is clear is that we no longer have a benign global public good - Gaia - offering a lavish world of non-rival consumption. Ten millennia of agriculture development and, most of all, a couple of centuries of industrial revolution have transformed it in a global common-pool resource - Gaia - where human actions show serious externalities on the ecosphere as a whole. Once understood that we are part of Gaia, the challenge is how to overcome the global collective action problems linked with the building of a long term equilibrium with it (i.e. sustainability).

Conclusion

This paper constitutes an attempt to link two different fields of human knowledge in the study of global environmental issues. Social and natural sciences do not often meet in the research agenda, nevertheless interdisciplinary work appears unavoidable for a better understanding of the relations between human beings and the environment. Tyler Volk (1998, 246-250) describes humans as "the guild that knows all other guilds", referring to it with the term, first introduced by the Ukrainian scientist Vladimir Vernadsky, of *noosphere*: the sphere of knowledge. Still, what we know is a minor part of what we ignore (in Volk's fancy dialogue with Gaia the *noosphere* soon becomes the *noodlesphere*), and ignorance can be easily enhanced by lack of communication among disciplines. We have tried to show that cross-fertilization can lead to valuable insights and that it could be worth walking in the long path of interdisciplinarity. To introduce Gaia theory elements in CPRs analysis has led to a better conceptualization of global commons and of the problems they pose. Unlike the case of "traditional" local scale resources, there is little possibility for trial-and-error institutional building experiments in our global common Gaia. This increases both the necessity of great cautiousness in any action to undertake (which is captured, for instance, by the precautionary principle) and the need of comprehensive models for the Earth system, which must include anthropic activities. A large amount of research is still necessary in order to build them, but some interesting programs are working towards this goal. A good example is Nasa Earth Observing System (Eos[18]), a comprehensive program based on satellite measurements and designed to improve the understanding of Earth as an integrated system. Its aim is to increase our awareness of "how natural processes affect us, and how we might be affecting them"[19]. According to Nasa, the program will yield "improved weather forecasts, tools for managing agriculture and forests, information for fishermen and local planners, and, eventually, the ability to predict how the climate will change in

[18] Just as Gaia, the Nasa program name took its name from a Greek goddess: Eos, the goddess of dawn.
[19] See http://eospso.gsfc.nasa.gov/

the future"[20]. Most of that appears valuable also for CPRs students. As many scientific enterprises, Eos will probably rise more questions than it will answer. Nevertheless, it will also help our understanding of Gaia, it will permit the construction of better global human-environment relationship models and, hopefully, it will at least partially respond to the growing feelings of urgency caused by the emergence of overwhelming global environmental problems. On a much smaller scale than Eos, our aim was to conceptualize Gaia as a new common, a complex one where humans are, at the same time, the appropriators and a part of it. At present humans are not enlightened managers of it. They look indeed much more like parasites that consume - for instance - more than 40% of the net primary production of their host (Purves *et al*, 1998, 1293 and 1349). We hope that a better understanding of the complex functioning of the Earth system will, among other, help the reaching of a better harmony with it.

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[20] See http://eospso.gsfc.nasa.gov/

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Tables

Atmospheric composition (% weight)	Mars	Earth	Venus
Carbon dioxide (CO_2)	95	0.036	98
Nitrogen (N_2)	2.5	78	2
Oxygen (O_2)	0.25	21	0
Water vapor (H_2O)	0.1	<1	0.05

Table 1: atmospheric composition of Earth, Mars, and Venus
(from Schlesinger, 1997, 41)

Country	Population (millions)	Ecological footprint (global ha p.c.)	Biocapacity (global ha p.c.)	Ecological deficit (global ha p.c.)
United Arab Emirates	2.6	10.1	1.3	8.9
Kuwait	1.8	7.8	0.4	7.4
Belgium/Luxembourg	10.2	6.7	1.1	5.6
United States of America	280.4	9.7	5.3	4.4
Japan	126.8	4.8	0.7	4.1
Netherlands	15.8	4.8	0.8	4.0
Israel	5.9	4.4	0.6	3.9
United Kingdom	59.5	5.4	1.6	3.7
Denmark	5.3	6.6	3.2	3.3
Central African Rep.	3.6	1.2	6.2	-5.0
Angola	12.8	0.9	5.9	-5.0
Canada	30.5	8.8	14.2	-5.4
Bolivia	8.1	1.0	6.4	-5.4
Australia	18.9	7.6	14.6	-7.0
Congo	2.9	0.9	9.1	-8.1
Papua New Guinea	4.7	1.4	14.0	-12.6
New Zealand	3.7	8.7	23.0	-14.3
Gabon	1.2	2.1	28.7	-26.6

Table 2: the highest and the lowest nations in the ecological deficit ranking, 1999 data
(source WWF, 2002)

Figures

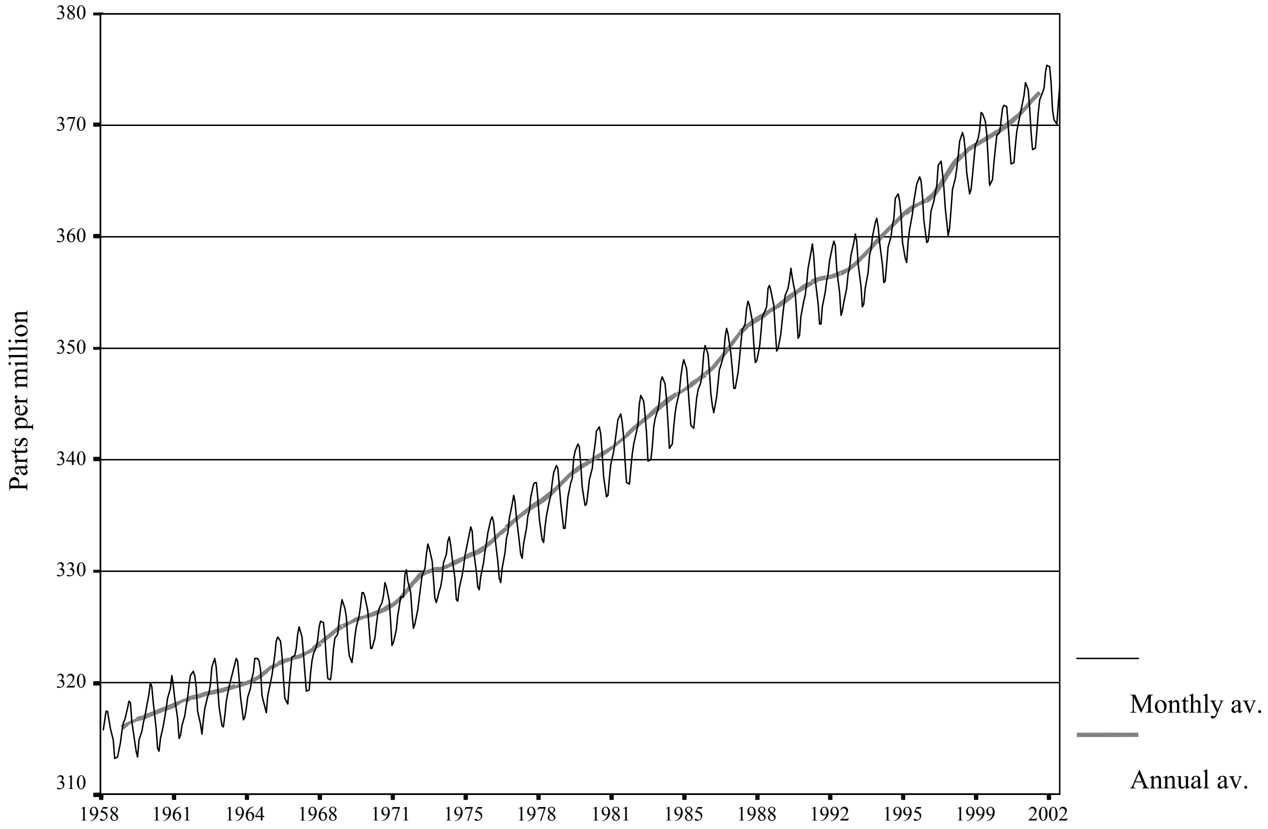
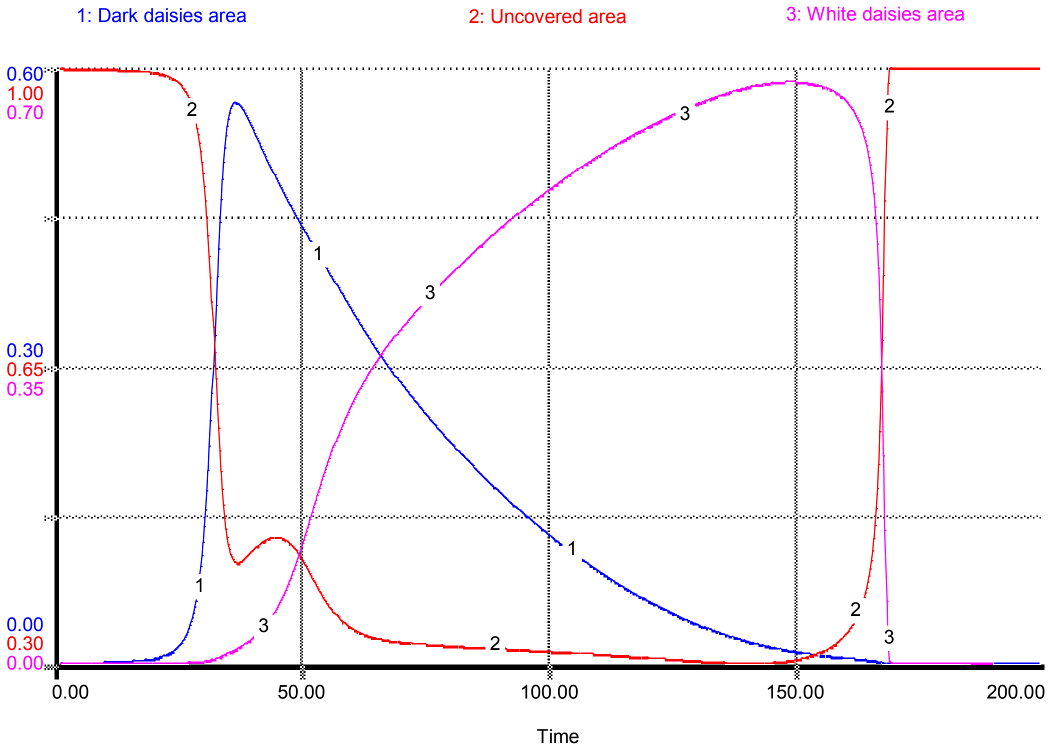


Figure 1: atmospheric CO_2 concentration in Mauna Loa, Hawaii, 1958-2002.

(source Scripps Institution of Oceanography (SIO), University of California) a)



b)

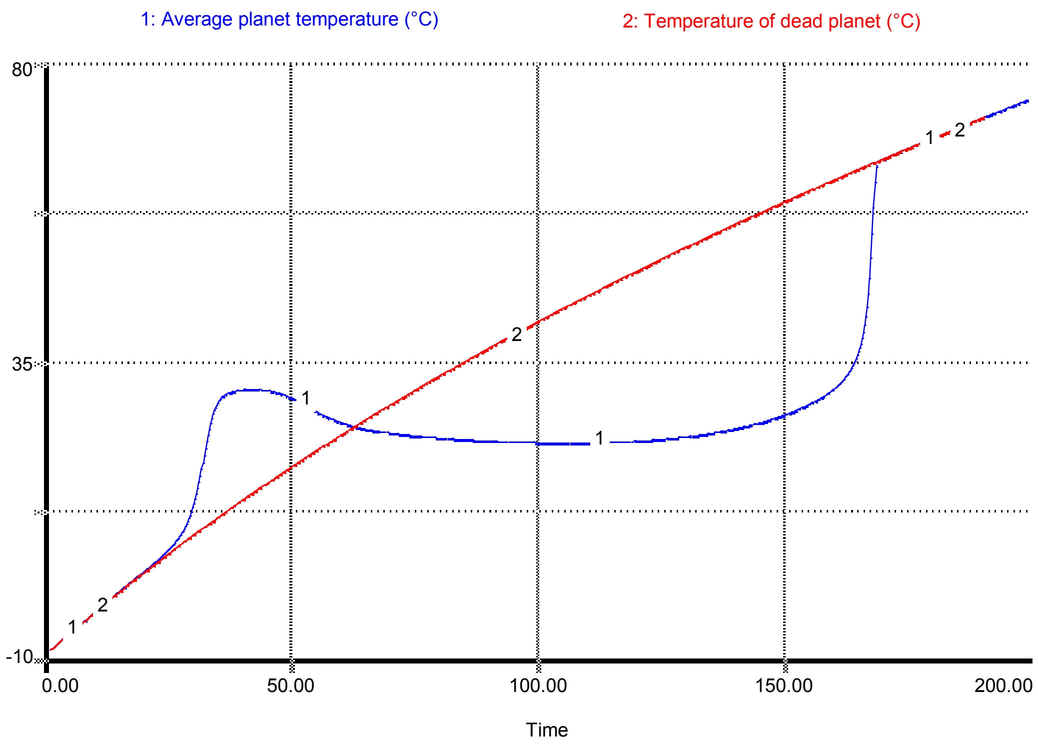


Figure 2: simulation results of a Daisyworld model

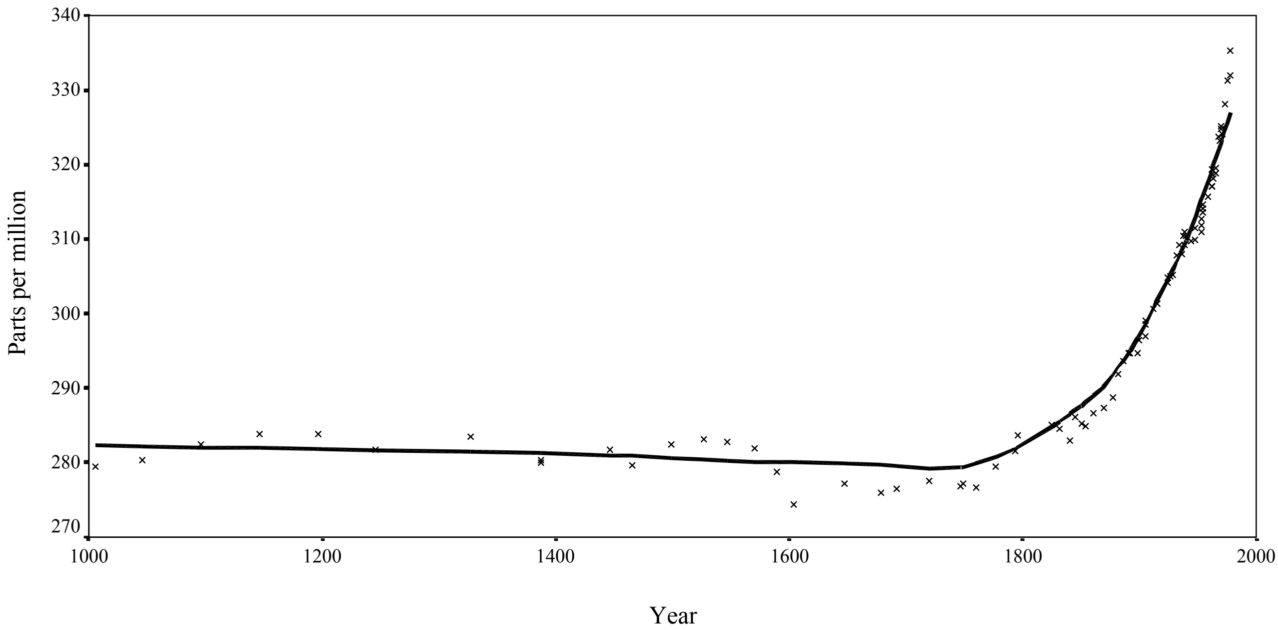


Figure 3: historic concentrations of atmospheric CO_2

(source Etheridge *et al.*, 1998)