UNDERSTANDING THE CONCEPT OF ROBUSTNESS IN SOCIAL-ECOLOGICAL SYSTEMS: DEFINITIONS AND EVALUATION

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Abstract

The purpose of this paper is to propose a procedure to evaluate social-ecological systems’ robustness based on a robustness definition that answers to three basic questions: (1) what is the relevant system to be studied?, (2) what are the desired system characteristics to be preserved?, and (3) when does the collapse of one part of a social-ecological system imply that the entire system loses its robustness? The proposed (tentative) definition is the following: a social-ecological system is robust if it is capable of supporting the current trend of population growth at the current levels of per capita use of the natural resources without it is necessary to change its basic rules in use. The system’s robustness degree at a particular time is given by the theoretical distance from actual conditions to its instability tipping point. A tipping point is a threshold condition that, when crossed, shifts the dominance of feedback loops that control the process. Social-ecological systems tend to remain stable as long as the conditions remain below the tipping point. But when conditions cross that point its behavior can become temporally unstable and system's robustness be disrupted. The proposed heuristic procedure to evaluate the robustness of local level SES is to compute the human ecological footprint of the system and to compare it with basic indicators, such as the arable land availability. It will be suggested that, by using this procedure, it is possible to identify if the system is below of its overshoot tipping point. This is an important signal because it indicates the existence of windows of opportunity in which perhaps it is still possible to reverse paths toward collapse in social-ecological systems.

Biography

Newton P. Bueno is an Associate Professor at the Department of Economics, Federal University of Viçosa/Brazil, in the areas of Macroeconomics and Institutional Economics. He received his Doctorate from the State University of Campinas – UNICAMP/Brazil - in 1996 and has been working mainly in the field of Institutional Economics applying the system dynamics methodology. Presently, he is spending a sabbatical year as visiting scholar at Workshop in Political Theory and Policy Analysis at Indiana University sponsored by The Coordination Agency for Improvement of Teaching Personnel (CAPES) of the Brazilian Government.
The idea that a social-ecological system (SES) can or not be sustainable, that is can or cannot preserve its fundamental properties over time, as implicit for instance in the UN Commission on Environmental Development’s definition of sustainable development\(^1\), is absolutely in itself plausible. The problem is that, at least until this moment, researchers studying SES’s have not yet reached an entirely convincing operational definition of the concept of sustainability (Gibson et al., 2005; Anderies et al., 2004; Hanley, 1998).

Today there seems to be, however, an increasing (implicit) consensus around the idea that sustainability, resilience or robustness (from now on I shall use the last term) are broadly similar or, at least, highly related terms\(^2\). The general meaning of those concepts is, to sum up, the capacity of the system to experience shocks while retaining essentially the same function, structure, feedbacks and therefore identity. The more robust a system, therefore, the larger the disturbance it can absorb without shifting into an alternate region (Walker et al., 2006, Walker, 2004). For instance, it seems intuitively plausible that a community can temporally operate above the level compatible with its natural resources endowment, using, say, water for irrigation and other purposes in amounts higher than that the system can recompose, reducing, in this way, the existing water natural stocks.

It is more difficult to define an unequivocal measure of robustness in SES when compared for instance with engineered systems (Janssen, 2006). For example, a SES can recompose its stocks of water after a severe drought, but it may be unable to recover the institutions that previously worked and that allowed a certain population to be supported by that system. In this case, the availability of water in itself is not a reliable indicator of the system's robustness. The shortage of water, however, can trigger cumulative processes that lead to institutional robustness loss, what may reduce the SES's population absorption capacity even after the shortage of water has been overcome.

An alternative definition of robustness that emphasizes the institutional aspects of the concept is given by Anderies et al. (op.cit, p.7):

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\(^1\) That definition is the follow: “Sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future.”

\(^2\) In that sense resilience, for instance, should be seen as an attribute of sustainable systems (Lélé, 1998, p. 232) or as a measure of robustness and buffering capacity of the systems to changing conditions (Berkes and Folkes, 2000, p. 12)
"… A Social-Ecological System is robust if it prevents the ecological system upon which it relies from moving into a new domain of attraction that cannot support a human population, or that will induce a transition that causes long-term human suffering"

Three questions, however, must be answered in order to reach a sound operational concept of robustness based on the definition above, as suggested by Anderies et al., 2004: 1) what is the relevant system to be studied?; 2) what are the desired system characteristics to be sustained, that is, precisely what is intended to be sustainable?; and 3) when does the collapse of one part of a social-ecological system imply that the entire system loses its robustness, that is how will sustainability be measured?

The objective of this paper is to propose a procedure to evaluate the degree of robustness of SES based on a robustness definition that answers these three questions. It will be suggested that SES lose robustness when they pass beyond tipping points. A tipping point is a threshold condition that, when crossed, shifts the dominance of feedback loops that control the process. Social-ecological systems, by this definition, tend to remain stable as long as conditions remain below the tipping point and controlling feedback is dominant. But when conditions cross the tipping point its behavior can become temporally unstable and system's robustness be disrupted (Sterman, 2000; Perrings, 1998).

In the section two, I start by discussing the third question above, presenting some examples which highlight the relationship between the ideas of vulnerability and robustness; the objective is to show that a system usually loses robustness after crossing critical resources usage tipping points. In the section three, a general model that describes the main properties of systems that follow the dynamics above is presented. In the section four, I discuss the second question trying to show how the concept of Human Ecological Footprint can be used to detect the presence of tipping points in irrigation systems, using the System Dynamics approach. Section five concludes the work, addressing the three questions jointly presenting an operational definition for robustness, as well as some implications of that definition, and suggesting a heuristic procedure for future studies.

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3 This seems to be one of the more unsatisfactory discussions in the literature; for assessments of the discussion on the principal topics involved see Eakin and Luers, 2006.
It is trivial to affirm that modern societies are highly dependent on computers, but perhaps it is less obvious the idea that, for that same reason, they are more vulnerable (or less robust) than 30 or 40 years ago to problems in that critical item of their infrastructure. At that time, computers were artifacts used only in hugely complex operations like space flights. Even so, the computer used by NASA to program the first manned flight to the Moon had only about 33000 words of memory, a small fraction of any modern desktop model (Chaikin, 2007). Today almost every important aspect of our daily lives are controlled by computers, from the airplane traffic and the operation of life sustaining equipments at hospitals, to the most prosaic activities. When, for instance, we enter into a Wal Mart store and acquire a television, at the same time an order is emitted and automatically transmitted to the contracted supplier, let us say in Malaysia, to begin the production of an additional item. The dramatic implication of that transformation is that, if on the one hand, the economy has become much more efficient and our life, more comfortable, on the other hand, the modern societies have become much more vulnerable to events that would have had very little impact in our lives 40 years ago, such as say a general breakdown on the net servers.

Something like that was very close to happening in 2000, due to the so called Y2K problem. The experts today consider that the correction of the year 2000 computer program was the largest technical project in the human history. If the computers using only two digits to represent years had not been adjusted, the world economy might have collapsed. In order to prevent this catastrophic scenario, about $500 billion were spent by private companies and governments to fix equipment (Schwaninger, 2005). Everyone knows that the problem was in the end satisfactorily handled, but this should not hide the fact that the Y2K problem was a clear manifestation of the vulnerability of the modern societies’ critical technological infrastructure.

Critical infrastructure's vulnerability had once much more dramatic consequences for one of the more developed pre-Colombian American civilizations. The Chaco (Anasazi) society bloomed during the years 600 and 1100 in the area that today is the State of New Mexico in the United States and disappeared abruptly in some moment between 1150 and 1200. It was an integrated and culturally complex society, capable to accomplish a sophisticated architecture and to develop an economy with division of the regional work, although it had not gotten to create or
to use a writing. Its achievements and final collapse are lessons that can be highlighted by a more operational concept of robustness.

The villages that constituted the Chaco society settled in an extremely fragile ecological environment, mainly in terms of water availability. To solve that vital problem, their inhabitants tried almost all the institutional and technical solutions that we can imagine that were available to them. In a first phase, they lived and planted in the highest lands where the rains were more reliable or in lower lands, where they were able to build extensive irrigations systems with hundreds of kilometers of secondary channels. In a second phase, they explored lands where groundwater was shallow, allowing the excavation of wells, using systems of land rotation to avoid the excessive impoverishment of the soil. Those solutions worked, while the population density was not very high, but they became unviable when the population started to occupy all the land available for agriculture. At this time, they developed a last innovation capable to be amazing, due to its sophistication, to the more optimistic of the institutional economists.

They constituted a regional economy in that the plantations were made in each village in order to minimize the uncertainty of the rain regime. Part of the crop was then distributed among the villages that had not had enough rain in a particular year. This solution requested the simultaneous development of a political and social system capable of integrating the activities among the several villages. This system eventually emerged, having the Chaco Canyon village as its center, which, like the great modern cities, became the political and cultural center of the society.

The problem is that a society like that can only work at a minimum size. It would be absurd to think that New York City, for instance, could survive if its population was reduced to a third of its current value. The reason is that it certainly would be economically and politically disintegrated before reaching this size, due to the high level of connectivity among functions and forms in systems such as huge cities like New York (for a discussion around this point see, for instance, Fraser et al., 2005). At first sight, we could only think in this scenario as an outcome of a great catastrophe like the shock of an asteroid. But it was something much more frequent in the humanity's history, although with similar reflexes, that led the society of Chaco to the collapse: a great drought occurred about the year 1130. The inhabitants of Chaco had already survived droughts many times in their history; the difference now was that the population had already passed through a threshold or tipping point until which it could have adapted itself to less favorable environmental conditions. Now, the system depended on an intricate network of economic and social relationships among the inhabitants of the several villages (a number of
important papers highlight the fact that more complex ancient societies became progressively more vulnerable to disturbances such as droughts; for a review of this literature, see Janssen and Scheffer, 2004). As the drought worsened, the people of villages that supplied the center with food, for instance, lost the faith in the priests' supernatural power and in their political leaders and started suspending the delivery of food. In doing that they reinforced the process of institutional collapse triggered by the drought. It is not known how the process unfolded in practice, but the fact is that probably between 1150 and 1200 the Chaco villages became completely uninhabited for more than 600 years until the Navajos occupied them again.

The history of the Chaco society, therefore, registers people's struggle to survive when placed in an unsustainable development path. It is possible to imagine that smaller communities could have inhabited the area for more time than the amazing society of Chaco. But it was the own ingenuity of the Chaco people in finding technical and institutional solutions for their fundamental problem - the shortage of water - that led to the population unsustainable growth and to the final disaster. As stated by Jared Diamond (p. 155): there were several immediate causes of the collapse in each one of the villages, as soil salinization and deforesting, but:

“... all were ultimately due to same fundamental challenge: people living in fragile and difficult environments, adopting solutions that were brilliantly successful and understandable ‘in the short run’, but that failed or else created fatal problems in the long run, when people became confronted with external environmental changes that societies without written histories and without archaeologists could not have anticipated.”

Are modern societies going through the same track followed by the Chaco society? An influential group at the Massachusetts Institute of Technology's researchers led by Dennis Meadows (2004) thinks so⁴. For them, the world population already has moved beyond the sustainable development threshold, that is, it is using the planet's natural resources availability at a pace that cannot be sustained. The graph in Figure 1, which describes the famous Standard Run of the model used in *Limits to Growth*, illustrates that situation.

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⁴ The problem today can be even more serious as put by Diamond (1994:369): “… all countries today depend economically on other countries for some essential resource, including food and energy. All countries today are interconnected through living together in the same increasingly polluted atmosphere and oceans. In the next century we risk more than just societies of fragile environments collapsing one by one. We also risk a collapse of world society, an outcome for which there are already warning signs.”
The concept of Human Ecological Footprint, created by Mathis Wackernagel (Wackernagel, 1994; see also Wackernagel, 1999; Wackernagel and Rees, 1995), refers to the amount of land that would be necessary to sustain a population in a certain environment.

FIGURE 1: HUMAN ECOLOGICAL FOOTPRINT IN THE STANDARD RUN SCENARIO

In addition it should be noted that the Human Footprint can be an important robustness indicator, as it will be better later detailed. For now, it is enough to underline that once the system has passed from the maximum point in the Human Footprint curve, the adjustment of the system proceeds through endogenous reductions of the cultivated land, that is, by decreasing the level of economic activity. Until this point, institutions are in principle able to adapt in order to reduce in a controlled way the environmental impact. From that moment on, as it would happen about the year 2020, the earth system would enter in its collapse mode, in which the main variables would decrease simultaneously in an endogenous way. As it is shown in Figures 2 and 3 the per capita food availability, the level of per capita income and the most general indicator of life quality would fall well below the levels reached in, for instance, 1960. It will be argued ahead that points like the year 2020 are tipping point of systems.
FIGURE 2: PER CAPITA FOOD AND GDP IN THE STANDARD RUN SCENARIO

FIGURE 3: HUMAN WELFARE INDEX IN THE STANDARD RUN SCENARIO
In the next section, a more formalized notion of the concept of tipping point is presented.

3 – Tipping points and systems’ instability zones

In the model below (see Randers, 2007) the fish population in a social-ecological system is represented by a level variable that accumulates the natural population growth less the amount fished in each period. The mark of two parallel lines on the arrow linking the variables “fish population” and “catch” means that the individuals adjust the amount caught when the fish availability varies, but they make that adjustment only after a certain time has passed. This dynamics is the same in all the situations in which a common resource base is exploited; that is, people try to adjust their resource using rate, but they resist in making the adjustment until the last moment.

The fish population dynamics is depicted in Figure 4.
When the rate of resource extraction (catch) is smaller than the re-growth rate the resource stock (fish population in the system) increases. This happens in the region where the regrowth curve is above the catch curve. However, if the fish population falls below a certain critical level, the tendency is that the process becomes unstable. The fish stock will continue to fall in the following periods. The reason being that below that threshold, the system's re-growth rate will be smaller than the rate of fish extraction.

Let us imagine a society like the one of Chaco. Initially, when the population is small, the rate of water extraction is small as well. That is the catch curve is well below of the blue line represented in Figure 4. This situation is depicted in the Figure 5, by the Total Catch: Low Population curve. In those conditions the critical stock level is much smaller than the shown in the graph for the higher population curve. This means that the system is capable of sustaining great variations in the availability of water generated by droughts without entering in its unstable regime. The larger the population, however, the higher the position of the catch curve and therefore the higher the level of the critical stock. That is, it will be more likely that a drought could push the system beyond its instability zone tipping point, in which water availability falls below the critical level. When this happens and the population does not adjust its use level, the
rate of resource extraction will become larger than the re-growth rate and water availability will continue to fall in the following periods.

FIGURE 5: POPULATION AND WATER DYNAMICS IN THE CHACO SOCIETY

That dynamics suggests that variations in the resource availability, such as the ones produced by droughts, will produce different effects on the system’s robustness, depending on the historical phase in which the society is in\(^5\). Communities will be capable of surviving severe droughts in certain times, but will be vulnerable to much smaller variations in the availability of water in others\(^6\). The degree of robustness of a system therefore is not always a fact given by the nature, but it depends on the distance that that system is from its instability zone tipping point, that is, the region of its dynamic phase space where its behavior becomes unstable. In the model

\(^5\) The following account, known as the Curse of Akkade and taken from Mesopotamian clay tablets dating from 2000 BC, indicates that this is not a problem faced only for contemporaneous societies: “For the first time since cities were built and founded, the great agricultural tracts produced no grain. The inundated tracts produced no fish. The irrigated orchards produced neither syrup nor wine. The gathered clouds did not rain…people were flailing at themselves from hunger.” (Abate, 1994, p. 516).

\(^6\) To compare this notion with the traditional view espoused by the most part of the economists, King (1998: 962, 964) used the following analogy: “According to this view [from the economists], the natural environment behaves like a ball at the bottom of a bowl. Humankind can improve the environment by pushing the ball out from equilibrium, but if the force is removed, the ball would fall back to its original conditions… [but] human action can make the ‘bowl’ that maintains current ecosystem conditions so shallow that a small natural disturbance can cause the ball to roll out of the bowl.”
presented in the next section, it is shown how the process of phase transition can occur in irrigation systems.

4- Vulnerability in water availability, growing human footprint, and loss of robustness in irrigation systems

The influence diagram below summarizes the dynamics of the irrigation model proposed by Sengupta et al. (2000)

FIGURA 6

IRRIGATION MODEL: DIAGRAM OF INFLUENCES

The system is composed by two groups of agents: A and B. The amount of water appropriated for group A, for instance, depends on the parcel of water they are able to appropriate (A: Water Share) and on the size of their irrigation equipment (Infrastructure). The larger the amount of water that the agent can access, larger the portion of irrigated land and the final production (the arrows marked with positive polarity mean that a direct relationship exists among the involved variables). Larger production levels usually mean higher profits and consequently better conditions to invest resources in the maintenance of the irrigation equipment,
after the deduction of the domestic expenses. The amount spent by group A on infrastructure
maintenance in the simulation model is given for:

“A: Actual maintenance” = MAX (0, MIN ("A: Before Maintenance Net Benefit"-A's Dom Exp,
"A: Maintenance Dues"))

That is, the largest between these two values: zero and either the smallest value among
the profit minus the domestic expenses or the value necessary to keep the equipment in
operational conditions. That means simply that, in normal conditions of profitability, the farmer
will pay his portion of the equipment depreciation. However, when the profit is reduced, after
deducting his domestic expenses, the farmer cannot invest the total amount required to recover
the depreciation of the equipment. In this way, the amount invested in equipment maintenance
would be determined by the resulting difference between the actual profit earned and the
domestic expenses.

The degree of robustness in the above system can be assessed in the following way: what
level of disturbance, droughts for instance, can the system support before the agents stop
investing the total amount needed for the integral maintenance of the infrastructure?

In Figure 7, two scenarios were computed. In the first one (drought) it was allowed that
the precipitation level randomly varied from zero to a maximum of 33% below a precipitation
level of 2000 mm3 per year, which is considered as normal. In the second scenario (severe
drought) a variation of 50% from the normal precipitation value was allowed.

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7 The simulation models are available by requesting them directly to the author
Although the variation on the levels of precipitation in the two scenarios is not significant in absolute terms, the effects of variation on infrastructure of the system are entirely different, as it is shown in Figure 8.

FIGURE 8: INFRASTRUCTURE CONDITIONS, A’S IRRIGATED LAND AND OUTPUT IN TWO DROUGHT SCENARIOS
That suggests that, in passing from the “drought” scenario to the one of “severe drought”, the system has crossed a threshold entering a collapsed regime, as it was described in the previous section. But it must be observed that this did not happen because the water availability was significantly smaller in the scenario of “severe drought”, but because the precipitation variation triggered feedback processes that led the system to collapse; that is the system became unsustainable not due a chronic shortage of water, but due the effect of draught on social feedbacks involved.

Let’s see in more detail how that happened.

The shortage of water in the scenario “severe drought” was serious enough to lead the agents not to pay adequate maintenance dues. From the moment that started happening on, the irrigation equipment began deteriorating, reducing the capacity of the farmers to irrigate their lands and therefore reducing their profitability. Henceforth, even if the precipitation eventually returned to the normal level, the reinforcement loop above would continue to operate until the complete deterioration of the equipment. Notice that, in those conditions, the drought was the factor that triggered the process, but the shortage of water is not a permanent condition of the system; in any subsequent point beyond the tipping point, there is no shortage of water at all. What was decisive for the loss of robustness was the crossing of an inferior limit in the availability of water. Which in turn led the agents to start disobeying the rule of paying the total required maintenance rates. Therefore, although the triggering factor had been physical, the process of loss of robustness should have been seen primarily as an outcome of an institutional loss of robustness.

The loss of robustness of a system however does not necessarily depend on the occurrence of exogenous triggering factor as suggested above. The system can cross its instability tipping point if the human activity produces changes in the environment that imply
less productive use of the rains (such as soil sedimentation). But this does not happen suddenly; probably there are always (delayed) feedback processes involved.

In the diagram below, based on the former presented irrigation model, the effect of environmental degradation upon the land productivity is modeled. As it will be shown, the decrease in productivity provoked by an increasing human footprint can lead to a situation where investment in infrastructure is not enough to guarantee sustainability.

**FIGURE 9**
**IRRIGATION MODEL: OVERSHOOT AND COLLAPSE**

In the left side of the diagram (equilibrium and collapse loop) the previous situation in which a disturbance disrupts the system’s equilibrium, turning it unsustainable, is reproduced. In the right side (overshoot and collapse loop), it is depicted a situation where the system is endogenously driven to its instability zone by human action. To sum up, the process is the following: the irrigated agriculture produces a series of negative impacts upon the soil, for instance salinization. Soil salinization occurs due to poor irrigation practices that elevate the level of groundwater basins bringing salt to the soil. Soil salinization is one of the major processes causing land degradation and decreased productivity. Therefore drainage canals, that prevent surplus water used in irrigation to reach the groundwater basins, are as critical for productivity as the irrigation canals that deliver the water to the fields (Saysel and Barlas, 2001).

If investments in land recovery, for instance in building drainage canals, are not made in the necessary amounts, the soil fertility will be reduced and so does the land productivity; this
The process has been modeled in this paper as an elevation on the Human Ecological Footprint index. The assumption being that when the necessary investments are not made, the farmers will need to use additional new lands to produce the same amount of product as before (due to the decrease of productivity). Additionally it was assumed that farmers decide the amount of investments to be made by observing the amount of loss of productivity. In figure 9 the negative polarity of the arrow linking the two variables means that the investments tend to increase when the fall of the productivity is noticed, but this happens only after a time delay among the occurrence of the fact and the implementation of the corrective action, that is the accomplishment of the necessary investments.

The problem is that, besides the delay mentioned above, a significant time lag usually exists between a rise on the Human Footprint and the fall of the land productivity, so that the progressive use of new lands can lead eventually to a widespread and abrupt fall in land productivity and hence in profitability; in other words, the process can assume the form of overshoot and collapse.

The graph in figure 10 illustrates that overshoot and collapse dynamics.

**FIGURE 10**

**OPTIMUM E TIPPING POINTS OF LAND UTILIZATION**
Low Human Ecological Footprint values mean that a substantial amount of available land still exists. When land used approaches the total lands available to agriculture, however, idle lands required for environmental equilibrium maintenance start to be used and the productivity begins falling. In order to maintain their revenues, the farmers increase their land use rate. From the year defined as tipping point on, the profitability falls below the level that allows the farmers doing the right investments for equipment maintenance. The equipment deterioration leads the amount of appropriated water to decrease and so the amount of land used, leading the Human Ecological Footprint to start decreasing. But from this moment on, the equilibrium and collapse loop is already operating, pushing the system to operate far from the original equilibrium, which will eventually lead to the collapse of the infrastructure. But that is not all: the graph also suggests that it exists, in general, a window of opportunity in which the agents can revert the collapse path by adjusting some of the behavior rules identified for Ostrom (1992, 1990) as important to irrigation systems’ robustness. For instance, by restricting the access of new producers or by defining new collective-choice arrangements that allow a simultaneous reduction of the level of economic activity. In this case, the system could still come back to its land utilization optimum level. After crossing its tipping point, however, the system enters in its collapse mode, in which the decrease on human footprint occurs because the economic activity has been reduced due to the fact that the previous governance structure, in which the economic activity is embedded, was already disrupted. In those conditions, the agents are already facing significant falls in profitability and exactly for that they are not maintaining the irrigation equipment appropriately. This suggests that, after the tipping point is crossed, it is much more unlikely than they are capable of doing the additional sacrifices to change the actual rules in use. The Figure 11 shows what happens to the irrigation infrastructure after the system entering in its collapse mode (around year 55).
It should be noticed that if the investments in soil recovery had been made (Right Investments Scenario), the amount of land employed would not have increased, or it would have increased much more slowly, and the effects above would not have been so serious. It could be noticed also that if there were no time delays linking the variables Human Ecological Footprint and Land Productivity it would be more likely that the farmers had done the necessary investments even if their profitability had fallen. A convincing body of literature supports the hypothesis that the agents do not fully realize the real length of the time delays involved very quickly (see, for instance, Sweeney and Sterman, 2000, and Jensen and Brehmer, 2003). The conclusion is that, in many social-ecological systems, the loss of sustainability can be a very slow process but that accelerates abruptly without being possible to identify clearly a disturbance strong enough to trigger that crisis. In the case of the society of Chaco examined in the beginning of this work something like that seems to have happened: despite of accomplishing the institutional investments to overcome the fragility of the physical environment in which they were located, they probably were not able to notice the much slower environmental degradation process that would lead their society to the final collapse.

Today there are straightforward procedures for computing systems’ tipping points. One of the simplest is that proposed by Ford (1999) and Taylor and Ford (2006), that allows to identify
the change of feedback loop dominance, by successively activating and disabling the principal
loops of a simulation model and verifying the effect on the variables of interest. But this process
requires the construction of simulation models what can be beyond the objectives of the
particular research. A simpler procedure would be to compute a simple indicator like the human
ecological footprint, as suggested in several recent works (see, for instance, Jenerette et al., 2006
the; Jenerette et al. 2006 b; Ferng, 2005; Gerben-Leenes and Nonhebel, 2002; Harbel et al.,
2001) and to evaluate whether the system is below or above its institutional instability zone. As
discussed before, this tipping point is reached when the indicator begins to fall after having
passed, for instance, the value of the total land available for irrigation and domestic use. Beyond
this point, decreases on human footprint index do not happen because the individuals adjust the
rules in use which structure their behavior, but because the system becomes unsustainable for the
previous governance structure. In other words, the reduction on the pressure upon natural
resources happens in that case because the institutional disintegration leads to the reduction on
the economic activity and hence on the level of resource use, as well as to an intensification of
the conflicts and to a significant worsening of living conditions.

5- Conclusion

The previous discussion suggests the following (tentative) definition for robustness of
social-ecological systems:

a social-ecological system is robust if it is capable to support the current trend of
population growth at the current levels of per capita using of the natural resources without
being necessary to change its basic rules in use. The system’s robustness degree is given by
the theoretical distance from the actual conditions to its instability tipping point.

A simple example can help explain the definition better. Suppose the following
scenario. A community of fishermen established over a long time in that the same place,
where researchers found that population size has been kept relatively stable, as well as the
amount of fish caught, let us say 150 tons for inhabitant/year. Finally, suppose that it was
identified that they go fishing just half of the days of the year, dedicating the remaining days
to equipment repairing, leisure and other activities. By definition the above system is robust,
because it is able to generate 150 tons of fish/habitant/year for an indefinite period of time ahead.

Now imagine a second scenario. Because of the use of a superior fishing technology from a neighboring community, the available amount of fish to the original community decreases. That would trigger here then a process similar to that described in the general model on section 2, namely the rate of fish extraction would become higher than the system's re-growth rate, what would lead the system to cross a typing point, beyond which occurs endogenously subsequent reductions in the stock of fish available. In this case, the definition above would indicate that the system would have lost robustness for the existing governance structure. That is if the rules used by the researched community are not modified, the system will become unsustainable at the present level of fishing, being unable to continue generating 150 tons of fish per person year, or even entering in a collapse path. If, however, the rules in use by the community are adjusted, reducing for instance the number of fishing days per year, it is possible to the system to become sustainable again, but at lower level of fish consumption per person.

It seems that this definition can, therefore, give a more operational content to the definition suggested by Anderies et al. (op cit) in allowing to answer in an unequivocal way to the three questions proposed by the authors, mentioned in the introductory section of this paper, namely: 1) the relevant system is composed by the people that live in communities that explore a common base of natural resources; 2) the desired characteristic of the system that should be sustained is the current level of per-capita using of the critical resource, for instance the per capita availability of water in an irrigation system and 3) the system will lose robustness when it passes through instability tipping point, for instance the Human Ecological Footprint curve's maximum.

From this definition the following hypotheses, to be tested appropriately by further studies, can be stated:

i) the process of robustness loss always involves a significant endogenous component, although such a process might have been triggered by disturbances such as exogenous natural shocks. The explanation is that although it is conceivable that the robustness of a system can be suddenly lost by the action of catastrophic exogenous shocks, as for instance the extinction of the
dinosaurs provoked by the shock of an asteroid on earth, those situations are rare enough so that we can discard them when studying the dynamics of social-ecological systems;

ii) the process of robustness loss always involves a key institutional component, although bio-physical factors may have an important role in triggering the process. This means that robustness loss nearly always happens in reason of the human action, in particular due to the incapacity of adopting or altering the rules in use which structure human behavior in a particular community. In the example of the irrigation model, the robustness loss can happen for two reasons: a) because the individuals do not accept making the appropriate irrigation infrastructure maintenance payments in drought periods or b) because the individuals do not invest enough in soil recovery;

iii) institutional (social and economic) feedback loops dominate the system's long term dynamics, for instance those related to the evolution of the investments in equipment maintenance or in soil conservation, as well as those related to the evolution of the level of conflicts in the use of water, which might suggest for instance a progressive mismatch of the system's governance structure.

iv) the use of bio-physical or institutional isolated indicators, as the availability of water for irrigation or the evaluation of the rules in use for a community, is a necessary but not a sufficient procedure for assessing the robustness degree of a social-ecological system. Based on the definition above it is necessary to incorporate in the same analytical framework the institutional and ecological dynamics involved in the process of loss of robustness.

A good procedure for assessing the robustness of a system, finally, is performing detailed studies on its feedbacks structure, seeking to identify the dominance ranges for each one of its principal loops, as well as to detect tipping points in which loop dominance shifts happen. This process is not excessively complex, being available relatively simple procedures to measure the distance a particular system is from its instability thresholds, that is its tipping points. However, as already mentioned, to build simulation models can be far beyond the objectives of specific works. A more accessible heuristic procedure for assessing SES's robustness is to compute some indicator as the human ecological footprint and comparing it with basic indicators, such as the amount of land available for the agriculture. Notice that in this case it is in thesis possible to infer, approximately, whether the system is still below the point in that the overshooting in the use of the resource happens. It may be possible in other words, infer if the human ecological footprint is below the maximum level of land using, beyond which reinforcing mechanisms will
lead to endogenous jointly decline of capital stock and institutions, upon which the communitarian life in the system was previously settled; this is an important signal insofar it could indicate us the time dimension of the window of opportunity in that perhaps is still possible to revert collapse paths in social-ecological systems.

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