

Review

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Review

Terraforming Earth—The Environmental Economics of Engineered Participatory Watershed Management in Ceará, Northeast Brazil

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Abstract: Brazilian watershed management councils offer an interesting environmental economics case study. They illustrate how the noösphere is a major force in environmental regulations that terraform surface topography. Across the state of Ceará, Northeast Brazil, democratic management system of watersheds, i.e., watershed management councils (WMC) promote scientific and democratic regulations of environmental relations: a clear case of the noösphere transforming the semiarid landscape into a fertile ground for agriculture. This paper discusses the environmental economics of the region by studying the noösphere using both institutional diagnosis and social network analysis. I argue that environmental and ecological discussions should privilege the category of “terraformation” over “adaptation”, especially now, in the Anthropocene. In other words, the increased dominance of mankind over nature would be better understood by treating democratic environmental governance and sustainable development as a kind of “ritual regulation” which shapes “environmental relationships”. The lessons from Ceará’s 38-year-old natural experiment could prove valuable for tackling the more pressing issues of environmental change and human collective action.

Keywords: anthropocene; environmental economics; human ecology; institutional approach; noösphere; social network analysis; terraforming; watershed management

1. Introduction

Environmental economics is grounded on an utilitarian worldview and, therefore, emphasizes the role of conscious economic activity on ecosystems as result of natural resource management and environmental policy. Conversely, the discipline of human ecology emphasizes the role of passive adaptive behavior [1-5] as the evolutionary mechanism of human economies within the context of natural ecosystems. Although there are compelling cases for the coevolution of human economies and natural ecosystems [5], MacCready’s [6] point about the shift from chance to human intervention as the primary driver of history and evolution seems more plausible when dealing with conscious niche-construction [7] at regional and global levels.

Implicit in the analysis of human evolutionary processes is the idea that human belief systems and rituals are akin to nonhuman animal adaptive behavior, i.e., an effect of material environmental pressures that all living organisms in the biosphere are subjected to. Despite controversies regarding causality in the social sciences, it is becoming increasingly clear that ideology and human belief systems are the driving force in human terraformation of the pedosphere. Biospheric pressures that shape Earth’s ecosystems become effects (or dependent variables) of human ideology and belief systems, which take the role of proximate causes in the Anthropocene. And when human agency imposes itself on physical and biological dynamics, i.e., terraformation, environmental issues become an institutional challenge.

Furthermore, rational economic behavior can only be measured within the context of a social, cultural, and political background. This means that environmental economics can benefit from

institutional frameworks and social network analysis that clarify the social, cultural, and political aspects of economic decision-making in a variety of different settings.

This paper discusses terraforming by contrasting three broad examples of how conscious human activity deliberately reshapes surface topography, highlighting the details of how this is done by focusing on the modern processes of terraformation in the semiarid backlands of the state of Ceará, Northeast Brazil. Section 2 discusses three case studies of economic and environmental ritual regulations at different scales. At the local scale of analysis, the Tsembaga horticulturalists of the Simbai Valley, in Papua New Guinea are discussed and at the regional scale two similar case studies of terraforming are presented, one with and one without the noosphere. First, the case of the Balinese farmers of Badung District, located in Indonesian province of Bali, and second the case of Ceará's noosphere and the terraforming of that semiarid landscape. Section 3 details the methods for studying the noosphere using both an institutional diagnostic approach and social network analysis. In Section 4, I bring a discussion of terraforming as a serious paradigm for studying environmental economics.

2. Materials and Methods

2.1. Materials

Here I will describe and analyze three different case-studies that explain the economy as a set of environmental relationships regulated by ritual. To understand what terraforming is and how it is done it is important to avoid the trap of focusing on the results of terraformation. Rather, we should focus on the driving mechanism stemming from human behavior that lead to terraformation at different scales. One of these cases fits the original concept of the noosphere [cite]. Therefore, a brief outline of what the noosphere is should set the stage for the discussion regarding each specific case presented below.

The noosphere can be understood as part of an evolutionary geological layer arising from a complex social network of interacting scientific human minds capable of impacting the natural environment [8] in ways thought impossible prior to the Industrial Revolution. Since the noosphere is a byproduct of the scientific and industrial societies, is the most recent sphere of geological activity. It can perhaps be dated to the Upper Paleolithic and the Out-of-Africa (OOA) migration of behavioral modernity of *Homo sapiens* but began in earnest roughly 12,000 years ago with the Neolithic Revolution [9] and continues up through the Industrial Revolution to the present day.

Already in 1968, Hardin [10] discussed the challenges associated with the restriction of freedoms in the context of common-pool resources and argued for some kind of morality that would grant a bundle of liberal freedoms in exchange for the unfreedom of biological reproduction. Since then, the mindset regarding population explosion as the single culprit of environmental degradation has abated but the structural aspects of the argument remained. If we accept that "the morality of an act is a function of the state of the system at the time it is performed" [10], then it seems necessary to understand how the material world is ideologically constructed. Furthermore, if today human behavior is a geological force driving evolution on the planet [9] and if such behavior is no longer bound by the adaptive constraints that our species experienced during the Holocene [11], then it is only by understanding how the noosphere operates and what came before it that we will be able to understand the different processes of niche-construction and terraformation.

To understand how the noosphere shapes the natural environment today I present two human ecology models that are especially useful for understanding human-environmental relationships from the perspective of "paradigmatic axioms" [12] of a culture that generate not only the rules [13] but also the kinds of rational behavior that are known and accepted by agents of a shared culture. Cultural paradigms can help us visualize how human ritual constructs the natural environment as a function of the ritual regulations that a particular culture produces at different scales and in different contexts. This contextualization improves our understanding regarding how terraforming is done in Ceará by providing a contrast with other cultures. In this section we will look at the ritual regulations

of the Tsembaga, a paleolithic peoples of Papua New Guinea, and the terraforming procedures of the Balinese rice farmers in Badung District.

2.1.1. Ritual Regulation of the Environment - the Tsembaga of Papua New Guinea

Terraforming among the Tsembaga of Papua New Guinea either does not exist or exists only to the extent that they clear native forests for their gardens and animal husbandry (pigs). Despite their negligible impact on the environment, they are an important case study for understanding the preconditions of terraforming by understanding the micro aspects of this pre-noösphere condition. The case study also reveals how the slow rise of the previously leads to changes in ritual regulations that in other societies and contexts can promote terraformation.

The “paradigmatic axioms” of their culture, what Hegel called *zeitgeist*, are centered on a political economy of ancestor worship, with their economic cycles operating in synchrony with their ritual cycles. Having only recently established contact with the outside world (first government patrol to penetrate their territory arrived in 1954), the Tsembaga have preserved a paleolithic way of life, numbering 204 persons in 1963. For this reason Rappaport (1967) [5] suggested they be treated as a “population in the ecological sense”, that is to say, an ecosystem of trophic exchanges in the boundaries of their territory, an area comprising of 8.29 square kilometers in the Simbai Valley of Papua New Guinea. As hunter-gatherer horticulturalists the extent of their terraforming was limited to bush-fallowing practices and the clearing of secondary forests from which crop producing gardens are cut and cultivated (this is the centerpiece of their paleolithic economics and warfare). Rappaport (1967) [5] estimated that the human carrying capacity of the Tsembaga territory was between 270 and 320 people, given the available calories from yam and sweet potatoes crops, and meat consumption that comes primarily from the sounder (i.e., group of pigs) population but also from hunting.

The pig population can and does vary, which means that finding the optimal size for the sounder (i.e., group of pigs) is difficult. Rappaport (1967) [5] explains that this optimal size is a function of stress. Stress is closely linked to labor and productivity [14-16] and will, therefore, affect the environment. We can imagine a kind of “ecological stress economy” that determines the state of society, i.e. war or peace, based on the number of pigs. If the number of pigs is small, the economy runs peacefully because pig-rations can be provided with minimal extra work and because the pigs practically manage themselves, running “free during the day returning to sleep at night” [5]. However, if the sounder grows large, the pigs become both a burden and a nuisance. It is a burden because labor is diverted from daily activities and because part of the harvest fit for human consumption is diverted for pig consumption, reducing the number of calories available and increasing the levels of stress in the human population. Furthermore, it is a nuisance because pigs start invading neighboring gardens, straining the relations between the pig owners and garden owners and increasing the chances of conflict in an already stressful situation. Under these circumstances, warfare seems like a viable solution to relieve the pressure.

As Rappaport (1967) [5] emphasizes, one can begin studying the Tsembaga adaptive and ritual cycles (unlike industrial societies these happen to be one and the same cycle) from any starting point. We can, therefore, present an outline of the Tsembaga cycle beginning with the “growth” phase of pig population. A small sounder tends to increase in size naturally because the Tsembaga almost never kill domestic pigs outside of ritual contexts. A tipping point is reached when the pig population exceeds the carrying capacity of human gardens, which causes pigs to seek out neighboring producing gardens that result in serious disturbances and conflicts. The situation can escalate to the point where the nucleated settlement disperses as people try to put as much distance as possible both between their pigs and other people's gardens, and between their gardens and other people's pigs. At this point, people begin to leave the territory, taking up residence with kinsmen in other local populations. Warfare eventually becomes a logical alternative for releasing pressure and reducing stress caused by the overpopulation of domestic pigs.

The details of warfare will not concern us here, but the end of hostilities is followed by the reorganization of society in a post-war truce marked by a series of rituals, which is enacted by the

victors and involves three major activities: (1) the ritual-planting of a shrub (i.e. the rumbim) which functions as a form of land demarcation of conquered territory; (2) a ritual-prayer to ancestral spirits whose function is to rearrange the group's relationships with the supernatural world; and (3) the kaiko a.k.a., pig festival where massive consumption of pork by all belonging to the victorious alliance and as repayment to ancestor- spirits for winning the war. Unlike the previous two, this last element has a direct impact on the "ecological stress economy" because meat consumption helps placate the problems associated with large sounders (i.e., garden destruction by pigs) and reduced calorie intake. At this point, the husbandry of pigs resumes and eventually the pig population increases, restarting the cycle.

Although this state of affairs can be explained in scientific terms as the result of trophic exchanges, it is certainly not the lived experience of the Tsembaga. The material "operational" model used by scientists for mapping the natural environment would, in principle, be sufficient to describe the Tsembaga adaptive cycle. However, without reference to these supernatural agents, there is no way to account for the "contracts" and the transactions characteristic of Tsembaga economy. For starters, the ancestors are the true owners of the land, where the living are only guardians or stewards of the land. This means that the transfer of property is really a transfer of an ownership entitlement between the ancestors of one group to the other. This means that Tsembaga behavior and economy only operate in relationships to a supernatural world order "cognized" in such a way that there is no distinction between the spiritual world and the natural environment. Under these circumstances it is very difficult to envision a different society capable of breaking out of the recurrent cycle of peace and war, since there is nothing one can do within this morality and mindset to alter the will of one's ancestors and the resulting stresses of naturally increasing pig population.

In conclusion, the ritual cycle of the Tsembaga is a paleolithic adaptive cycle at the level of the biosphere. However, as human societies there has always been some form or another of niche-construction. In the case of the Tsembaga time flows in a circular pattern generating a steady-state growth economy at the local scale. Strictly speaking, such a culture does not terraform the environment but does have the potential to evolve into a society that would have such capabilities, granted their moral characteristics undergo a paradigm shift associated with the buildup of increasingly complex social orders [17] such as those experienced by neolithic or industrial societies. Such societies often abandon the paradigmatic axioms of Tsembaga culture transitioning from a steady-state economy and ecological homeostasis to one centered on ritual cycles of entropic economic growth. In the next subsection we will look at another case of ritual regulation of environmental relationships that is also pre-noösphere but capable of pre-industrial terraforming of their environments.

2.1.2. Ritual Regulation of the Environment - the *Subaks* of Bali

Tsembaga culture has never produced a noösphere which would render it capable of terraforming the natural environment. Pre-industrial Balinese farmers have terraformed their environment [7] without producing a priori a noösphere [8]. Unlike the Tsembaga, however, they transitioned from a paleolithic to a neolithic mindset around the 10th and 11th centuries [7]. The case presented in this section focuses on the cultural aspects of Balinese water management systems, i.e., subaks, where rice farmers ritually manage the regional network of "water temples" used for paddy field irrigation in Bali's Badung district [18]. These subaks are associations of farmers who manage irrigation systems, often in the watershed of their own village, but occasionally these associations would manage irrigation in more than one village.

As Fox and Lansing (2011) [7] explain "Subaks are self-governing assemblies of farmers, which hold regular meetings". These assemblies were responsible for the performance of calendrical rites in water temples, which are the primary coordination mechanisms for the highly synchronized schedules for efficient water distribution. As with many governance mechanisms, the subaks had governance rules [13] for managing their common water source and physically fragile tunnels, canals and aqueducts, of their irrigation systems. Extending several kilometers, this irrigation network

system required constant maintenance and collaboration, leading to a keen awareness of their shared interdependence but also to a backup regulatory mechanism grounded on the use of punitive fines and sanctions for members who do not abide by collective decisions.

A key feature, when trying to understand the construction of Balinese rice farmer's paradigmatic axioms, speaks to an adaptive necessity associated with Bali's topography: the way irrigation canals is distributed "makes it impossible for irrigation to be handled at a purely community level" [7]. Another important point is that, in principle, each subak could function as a completely autonomous rice irrigation unit, if rice was planted once a year. Since Balinese farmers did not develop rice storage technologies, they became accustomed to planting two rice crop harvests a year. The production of crops during the rainy season was not an issue. The problems arise when planting happens in the dry season because the absence of rainfall means that some kind of coordination or scheduling mechanism needs to be developed. To achieve this, it was necessary for the Balinese to create a culture that made possible the emergence of coordinated regional networks of "water temples" that exist today. Thus, in the pre-modern context under which this Balinese culture evolved their ritual regulations of their terrace ecosystems, the emergence of the subak permitted a very precise alternation between wet and dry phases are necessary for rice to thrive. It is this management of rice paddies and the that ensures good crop yields.

Interestingly, in other regions of Southeast Asia, the spread of irrigated rice agriculture is correlated with the expansion of precolonial kingdoms. Bali is different in this regard because the water management culture and irrigation systems arose bottom-up from hamlets and villages. Fox and Lansing (2011) [7] even present genetic evidence for this thesis concluding that "a process of niche construction pursued by generations of farmers, rather than the execution of a royal blueprint for the expansion of irrigation". It is true that Balinese rulers established Hindu and Buddhist monasteries, but these religions play little or no part in the water temple rituals. The water deities that actually are referenced in temple rituals are only instrumental names that serve a function of registering the annual calendar's agrarian rites, just as English-speaking cultures refer to Wednesday (i.e., Odin's day) or Thursday (i.e., Thor's day) as a day of the week without any spiritual connection to those divinities.

The key point of Balinese irrigation systems is that the high levels of cooperation, planning and social investment that are required to sustain it are secular but not modern, in the sense of functioning as a democracy or a scientific mega project. Irrespective of this, the approximately 19,000 hectares of the Badung irrigation network [18] could potentially produce around 59,000 metric tons of rice, which in turn could feed around 1.6 to 2.1 million people for a year, based on an average daily rice consumption of 200 to 300 grams per person.

Although the two case studies are radically different in scale, they share an important fact about terraformation: that the collective mindset is the cause, not the effect, of environmental conditions. This point is crucial for understanding the case of Ceará's terraformation of the state's semiarid environment and the transformation in living standards that this process has produced.

2.1.3. Ritual Regulation of the Environment - the 'Water Parliaments' of Ceará

The semiarid Northeastern Brazilian state of Ceará has a historical record of debilitating droughts. Such events were so prevalent in Northeastern Brazil that the region's aesthetic throughout the 20th century was one of social backwardness and economic underdevelopment. To understand terraforming in the case of Ceará, it is necessary to understand the paradigm that sets the boundaries for rituals - social, political, and economic - that regulate human-environmental relations.

Geographically speaking, Ceará is a state with low water availability, due to the combination of a series of factors, mainly: a single rainy season in the spring, low precipitation rates (less than 900 mm); high evaporation rates (greater than 2,000 mm); irregularity of the precipitation regime (frequent and sometimes multi-year droughts); and an unfavorable hydrogeological context (80% of the territory is on crystalline rock, with a shallow soil layer and few underground water resources).

Therefore, most rivers are naturally intermittent, that is, they are bodies of water that dry up during the dry season if they are not made permanent by regularization reservoirs [19].

Crises resulting from water scarcity as a function of droughts marked Ceará's development cycles with recurrent collapses in economic production, which in rural areas often led to starvation and famines [20]. The main coping mechanism of populations living in these conditions has been mass migrations [21] to other regions of the country. These facts are widely documented in reports of droughts such as those of 1877-78, 1887-90, 1915, 1919, 1932, 1958, 1970, 1981-83, 1998, 2012-2017. What the terraforming of the state has done in these last 38 years is to change the entitlement mapping [20] to the point where the most vulnerable populations no longer need to migrate as a strategy to avert the risk of starvation and economic collapse due to drought.

Despite not being fatal, droughts today still produce significant negative effects and due to their multisectoral scope and potentially catastrophic severity, droughts cannot be treated just as a hydrological risk impacting the quality of life and economic development of some populations. Drought must be seen as a systemic risk in the regional context, and since the volatility of the system is continuous and perpetual tackling the problem from an adaptive perspective only leads to palliative solutions. In fact, there are two fundamental problems with the adaptive perspective, respectively associated with spatial and temporal scales.

At the spatial level of analysis, severe multi-year drought events can dry up all but the largest reservoirs. It is, therefore, necessary for reservoirs to be connected via a transport network of water-mains that can take water from one local area to the next. At the temporal level of analysis, severe multi-year drought events followed by extreme rain events imply that dams must be capable of transporting water from rainy years to subsequent dry years. This is no mean feat since evaporation of reservoir lakes imposes significant water losses in the transport of water from one reservoir to the next, a hurdle to the strategic multi-year regularization of reservoirs based on their regularization capacities. In short, mitigating the impacts of these events has been an intergenerational challenge for the people of Ceará.

Realizing these challenges academics, researchers, policymakers, stakeholders, and a significant part of civil society have come to an increasing understanding of the need to change the environment itself. One of the architects of the hydrographic network mega project, Souza Filho (2022) [19], has said that recognizing the patterns of these recurrent extreme events must be the path to be followed to reduce the social vulnerabilities arising from these risks, and that this has been the trajectory of Ceará's society since the last five decades.

In this section, I will detail the construction of the noösphere and the subsequent process of terraforming the semiarid landscape of Ceará. It is important to emphasize that Ceará's efforts to mitigate the effects of drought on economic activities and human populations it is not just about the construction of water supply infrastructure (reservoirs, canals and water mains); it is also about reorganizing the environment to reduce the vulnerability of economic organizations (orienting the economic profile towards commerce, tourism and industry and transforming agriculture through irrigation) by managing water resources. We are dealing with an approximately 40-decade-old experiment in semiarid landscape terraforming, not a natural experiment [22] but a field experiment [23] of epic proportions. The goal of this section is to explain how the noösphere emerges with the implementation of a state-wide water resource management system [19, 24] and how this hydrographic mega project [25] has become a geological force in the region.

The starting point would be the fact that democratic watershed management is ingrained in Brazilian law; it is the foundation of the paradigmatic axiom for water management in the country. The re-democratization process experienced by the country, after a period of military dictatorship (1964-1985), led to the Constitution of 1988, which transferred the responsibility for watershed management from central state power to the 26 Brazilian states. This gave each state the autonomy to devise and implement its own watershed management policies, which is ideal for understanding the differences in regional mindsets that lead to successful or unsuccessful modern hydrographic management from the perspective of environmental economics. For example, Ceará shares principles

with the national water management model and, unlike other regional policy players that share a similar view, places enormous value on public participation in the process of water allocation and the relevance of recognizing water's value as an economic resource. Furthermore, Ceará's model differs from the national model with regards to the role of the basin agency, the forms of decentralization of management and the charging of water for the water supply service. However, this mindset centered on democracy and participation is not enough to ensure a noösphere. A modern bureaucracy grounded in environmental and water resource scientific research [26] is also needed.

The scourge of drought triggered both the state and the federal governments to think development programs capable of addressing the serious problems of migration and famines that have historically plagued the Northeast of Brazil. The state of Ceará developed a program based on a state-wide water storage system composed of hundreds of reservoirs that now dot landscape interconnected by countless canals and water mains. Together this physical infrastructure for water storage and transfer (the entire water infrastructure concentrates a multi-year reserve capacity of 18.93 billion m³) has ensured water security for the state's 8.95 million inhabitants across the state's 12 hydrographic regions. In regular years, the largest reservoir system in the state has a water release capacity to transform three major seasonal rivers into permanent rivers running year-round. Water is used for irrigation of various crops as well as human consumption and this hydrographic network has not only increased society's resilience to droughts, especially that of the poorest and most vulnerable segments of the population, it has also allowed for continuous economic activity during periods of scarcity.

The water resource infrastructure is only the most visible aspect of terraforming. A specialized system for water resource management with a well-defined political, legal and institutional framework was also deliberately planned and developed in the State of Ceará. It is an autonomous water resources management system but also integrated with the National Water Resources System and emerges from the strategy of mitigating the effects of drought on industry, commerce, tourism and irrigated agriculture.

In a way similar to the subaks of Bali (described in the previous section), Brazil's water management is decided in participatory water-basin management councils, a.k.a. watershed management councils (WMC) or "water parliaments", which were first established in 1994 as part of a state-wide policy to decentralize a state-centered water-management structure. They are composed of water users, civil society, and representatives of key institutions and work as a professional voluntary group bound in a polycentric [26] structure of governance similar to the Balinese Water Temple (also described in the previous section). The WMCs were designed to function as part of a broader structure that involves engaging water stakeholders of each watershed to make decisions "regarding reservoir allocations, which are based on volumes in storage and expectations regarding climate conditions for the following year" [24]. For decisions regarding the stored water volumes the WMC rely on expert knowledge provided by the state's water-resources management company (COGERH). Similarly, for decisions regarding climate conditions in the following year, the WMC relies on the state's meteorological research center (FUNCEME). This scientific support for WMC decision-making is provided to all 12 watersheds of the state. However, the WMCs are the only decision-making bodies with the attribution of deciding the operating rules for major supply reservoirs, decisions which directly or indirectly affect every stakeholder in that watershed (or possibly in other watersheds when a severe drought calls for the transfer of water between two or more reservoirs).

The resulting economic transformation experienced by the state as a result from this terraforming process is undeniable. To take a simple example, the Serra da Ibiapaba Watershed is today the largest producer of acerola in Brazil and hosts the largest manufacturer of Vitamin C producer in the country. Furthermore, the region is also a leader in fruit and fish production with cashew and carnauba ranking number one in terms of exports. Agribusiness, today, roughly corresponds to 25% of the region's GDP. All of this is the result of a terraforming process that is not simply about a series of water infrastructure mega projects, but also about creating a culture of

transparency and fairness grounded on scientific procedures assessment and deliberation of efficient water allocation.

Understanding that rituals are the key to terraforming the Brazilian semiarid and the history of how it happened, still does not tell us how it works. Using tools from common-pool resource governance [27], the next section presents a diagnosis of the noosphere, detailing the environmental economics of ritual regulations [5].

2.2. Methods

Here I will describe a method that can be used to visualize the noosphere. It relies on an institutional diagnostic approach and a special form of social network analysis, one that maps relationships between factors rather than agents. The focus here will be on Ceará since only the Ceará case fits the original concept [cite].

Ceará's socio-hydrographic network system is an example of how the noosphere is the major force driving terraformation on the regional level. Studying it from an environmental economic perspective requires an understanding of how the paradigmatic axioms of that culture manifest as rules, conduct, behaviors, and actions. Institutional diagnostics frameworks and social network analysis can be used to map the relationships between the various variables that make up the socio-hydrographic network system. In this section I look at how this network was constructed and how it operates on a single watershed of the state of Ceará: the Jaguaribe-Metropolitana Watershed.

Elinor Ostrom's institutional diagnosis is the primary theoretical framework academics and policymakers in the state today [28] because it organizes the multiple variables of a complex network of interactions and generates information about the behavior and resilience of the entire system. Optimizing the number of variables needed to describe the causal relationships of a "water network" is the central challenge of any diagnosis of human-water systems, but it is the best way to study the system's long-term stability. For example, Ceará's human-water system has 59 relevant variables [29] and a system with only 35 relevant variables would exhibit an exorbitant 75,525 different governance systems to analyze [30]. At present, we have neither the computational capabilities nor the human capacity to analyze this number of possible governance systems to determine the optimal one. Thus, it is necessary to restrict the number of variables and interactions of complex governance systems to model and analyze them.

Frota et al. (2021) [31] developed a diagnostic technique based on social network analysis (SNA) that establishes relationships of influence and dependence between the variables of a socio-water network. SNA explains how the various variables of a complex system depend on each other and how these interdependent relationships generate impacts that reverberate throughout the system due to the degree of influence and dependence of each variable. The interesting thing about the model by Frota et al. (2021) [31] is that the methodology relies on the institutional diagnosis of agents capable of determining, in order of importance, the most relevant variables for understanding the behavior of the system. Following the work of Ostrom (2007) [27] we can produce a diagnostic framework to describe the structure and functioning of the watersheds of the state of Ceará. It is based on this diagnosis that it becomes possible to optimize the management of water resources in the state with a view to developing efficient public policies.

2.2.1. Review of the Institutional Diagnostic Approach to Human-Environmental Systems

The interaction between the variables of a system can be interpreted as a network of relationships whose outcomes direct the evolution of the system itself. One can imagine countless variables for the most diverse SESs, but Ostrom (2007) lists some variables as being common to a range of different systems, which are reproduced below:

- Political, Economic and Social Scope (S): S1- Economic development. S2- Demographic trends. S3- Political stability. S4- Government settlement policies. S5- Market incentives. S6- Media organization.

- System Configuration (C): C1- Type (e.g., water, forests, pastures, fisheries). C2- Clarity about system boundaries. C3- Size. C4- Human facilities. C5- System productivity. C6- Equilibrium properties. C7- Predictability of system dynamics. C8- Storage characteristics. C9- Location.
- Governance (G) G1- Governmental organizations. G2- Non-Governmental Organizations (NGOs). G3- Network structure. G4- Property rights system. G5- Operational rules. G6- Collective choice rules. G7- Constitutional rules. G8- Monitoring & sanctions processes.
- System Resources (R) R1- Mobility of the resource. R2- Growth and replacement rate. R3- Interaction between units of the resource. R4- Economic value. R5- Size. R6- Differentiation markings. R7- Spatial & temporal distribution.
- Users (U): U1- Number of users. U2- Socioeconomic characteristics of users. U3- History of use. U4- Location. U5- Leadership/entrepreneurship. U6- Norms/social capital. U7- Knowledge/psychology of actors. U8- Resource dependence. U9- Technology used.
- Interactions (I): I1- Level of extraction of different users. I2- Exchange of information between users. I3- Deliberation processes. I4- Conflicts between users. I5- Investments. I6- Lobby.
- Outcomes (O) O1- Social performance measures (e.g., efficiency, equity, accountability). O2- Ecological performance measures (e.g., excessive extractivism, resilience, diversity). O3- Externalities of other socio-ecological systems.
- Ecosystem (E) E1- Climate patterns. E2- Pollution patterns. E3- Flows into and out of the local system.

This list of variables allows the construction of a socio-environmental matrix capable of describing numerous socio-environmental systems. In the next section, I provide two cases to show how it can be used, alone and in conjunction with social network analysis, to visualize the noosphere.

3. Results

Ostrom (2007) [27] exemplifies how a diagnosis can be made by constructing a systemic matrix of the thought experiment proposed by Hardin (1968) [10], in his description of the “tragedy of the commons”.

In his “allegory of the pasture,” Hardin (1968: 1244) [10] imagined a finite pasture area capable of providing sustenance for a limited number of animals, but with no restrictions on entry. Since it is open to any farmer who wishes to fatten his animals, it brings a direct benefit to the farmer of one unit of value per head of cattle and an indirect cost of a fraction of a unit of value, shared with all other farmers in the region. As rational economic agents, each farmer will calculate that the pasture supports the fattening of his entire herd, and in his own interest, the predatory exploitation caused by including all the herds of all farmers will lead to the collapse of the pasture through predatory grazing.

This “allegory of the pasture” can be expressed in a diagnostic framework using five variables: (i) the resource system is pasture (C1); (ii) no governance system is present (absence of G variables); (iii) the resource has individual and mobile units, cattle grazing on the pasture (R1), these units can be identified and are privately owned by farmers (R6), and can be sold for money (R4); (iv) a number of users (U1) greater than the size of the pasture (C3), which adversely affects the productivity of the area (C5); and (v) users are endowed with the psychology of the private economic agent and make decisions independently to maximize their own short-term returns (U7). These five assumptions about variables lead to a prediction of predatory exploitation of the pasture (I1) and, consequently, the destruction of the ecosystem system (O2). Thus, what Ostrom (2007) [27] does is organize the variables of the system characterized by Hardin (1968) [10] into a framework that diagnoses how this system should evolve given the premises presented.

3.1. Variables Selected by Ostrom to Describe Hardin’s “Allegory of the Pasture”

The diagnostic framework above shows the “allegory of the pasture”. From this diagnosis, it is possible to move on to the second stage of the analysis: the correspondence between the tragedy of

the commons thesis and the pasture systems that exist in the real world. To test the diagnosis in Table 1 above, Ostrom (1992: 413) [32] used focus groups to conduct experiments that controlled for the social capital variable (U6) via restrictions on face-to-face communication between participants. The experiment involved choosing between investments that gave different financial returns based on cooperation between agents. The results showed an increase in financial returns from 35% to 99% when participants’ decisions were made with face-to-face communication. This increase occurred because participants were able to encourage compliance from each other during face-to-face discussions by defining not only what each person would do, but also what everyone else should do. In other words, the implicit fallacy in the “pasture allegory” lies in the assumption that agents do not communicate and, therefore, do not have social capital (U6) to construct operating rules (GS5) capable of guaranteeing the rational exploitation of resources.

Table 1. Variables describing “tragedy of the commons” (adapted from Ostrom, 2007).

Political, Economic and Social Scope (S) S5- Market incentives	System Configuration (C)	
	C1- Sector	Governance (G)
	C3- System size C5- System Productivity	
Ø	Pasture (C1) Finite (C3) Renewable resource (C5)	Ø
System Resources (R) R1- Resource mobility R4- Economic value R6- Differentiation markings	Users (U) U1- Number of users U7- Psychology of actors	Interactions (I) I1- Level of extraction of the different users
Animal mobility in a defined pasture area (R1)	Large number of users (U1)	Maximum level of exploitation by each livestock user (I1)
Value of the product depends on the fattening of the animals (R4)	Short-term profit maximization	
Each user's cattle are distinguished by specific markings (R6)		
Outcomes (O) O2- Ecological performance measures	Ecosystem (E)	
Ecological system collapse (O2)	Ø	

3.2. Variables Describing Ceará’s Terraforming by Water Networks

Using this same framework, UFC researchers constructed a diagnosis of the socio-water system of Ceará (Frota et al., 2021) with the relevant variables for the scenario-based analysis of water resource systems in Brazil (Nascimento et al., 2010). To select those variables that strongly impact the water system of the region that connects the Jaguaribe river basin with the river basin of the Metropolitan Region of Fortaleza, a technique based on SNA was used to determine both the degree of influence and the degree of dependence of the system variables. A network of relationships emerges naturally where the combination between the degree of influence and dependence of the variables allows a classification of the variables as: (1) output; (2) input; and (3) relay [31]. Input variables (i.e., high influence and low dependence) are independent variables and affect the behavior

of the system unilaterally. Only climate variables (E1) and legal certainty variables (S1) fit into this category. On the other hand, the so-called relay variables (i.e., high influence and high dependence) are feedback variables, that is, their high influence on other variables, as well as their dependence on the behavior of the system, can affect its equilibrium. Conflict (I4), demand (I1) and supply (R2) with regard to water resources are examples of relay variables. What should be emphasized in this type of analysis is not so much the classification of these variables as input or relay, but rather that the socio-water system reveals itself as a network of socio-water variables, which interact and produce outcomes that can be scenario-oriented. For example, a simplified version of the Jaguaribe-Metropolitana water resources system (Table 2) can be constructed using the diagnostic framework that explains which are the relay variables and which are the input variables.

Table 2. Selected variables of the Jaguaribe -Metropolitana water resources system.

Political, Economic and Social Scope (S) S3- Political stability/legal security (noösphere)	System Configuration (C) C4- Human facilities (terraforming)	Governance (G) G3- Network Structure (noösphere)
Laws, SIGERH, etc. (S3): input variable	Water infrastructure (C4): feedback variable	Integrated water resources management system (G3): input variable
System Resources (R) R2- Growth or replacement rate (terraforming)	Users (U) U7- Knowledge of stakeholders (noösphere)	Interactions (I) I1- Extraction level of the various users (terraforming)
Supply of surface water (R2): feedback variable	Training for water resources management (U7): feedback variable	Water demand (I1): feedback variable
Outcomes (O)	Ecosystem (E)	
O1- Economic performance measures (terraforming)	E1- Climate patterns	
O2- Ecological performance measures (terraforming)		
Economic growth (O1): outcome variable	Droughts (E1): input variable	
Increased surface water supply (O2): feedback variable	Floods (E1): input variable	

Table 2 shows the most relevant variables of the socio-water network that configures the Jaguaribe-Metropolitana water resources system. This parsimonious configuration of the socio-water network is not ideal for carrying out a diagnosis of the system based on retrospective analyses, but it is ideal for the prospective study of the system's evolution. Frota et al. (2021: 11-12) [31] were able to demonstrate that the variable Integrated water resources management system (G3) is the only a variable that presents the second highest degree of dependence – behind only human supply (O2a) – in the Jaguaribe-Metropolitana socio-water system. However, the management of the conflict between water users can be treated as a O2b variable for prospective purposes, since the focus of the analysis is centered on understanding the future outcomes of the system, and not on the interactions that occur in the present. Another relevant finding, associated with the first, concerns the degree of centrality of the conflict. In SNA, centrality measures the influence that each variable exerts on each other variable in the network and, therefore, the impact that each variable exerts on the structure of the system as a whole [33]. Thus, centrality is a measure of the structural importance of a variable, given that its removal or translocation could result in the collapse or reconfiguration of the entire

system. Likewise, a variable that presents low centrality can be removed from the network or reallocated to any other position, without this generating any harm or consequence for the system. As it is the most central variable, given its high degree of both influence and dependence, conflict can be interpreted in the context of the Jaguraribe-Metropolitana system as the most important variable for its stability and is this capacity to shake the structure of the entire system.

4. Discussion

The transition from the Holocene to the Anthropocene may still be a hot topic of debate amongst geologists, but other scientists view the rise of the noösphere as a mark of the transition. We should revert our attention to the fact that we are living in an age that can be referred to as ‘the Anthropocene’ regardless of whether the International Commission on Stratigraphy [11] accepts this term as a new geological epoch separate from the Holocene. And, in practice, this means that the focus should be on understanding how the noösphere [8] increasingly determines environmental regulations [5] according to specific moralities. Only by understanding how humanity uses its powers of reason to terraform the planet can we design the social rules and cultural norms necessary for long-term sustainable development.

Terraformation has increased the carrying capacity in very distinct landscapes, from the wetlands of Bali to the semiarid backlands of Northeast Brazil. In both cases there has been economic growth without jeopardizing regional sustainability in the short-term. If the noösphere is constituted by the interaction of human minds, the question one needs to ask is how exactly this interaction between human minds result in environmental regulation of the pedosphere. The specifics will vary from case study to case study because the key aspect to studying the noösphere is causality, i.e., the deliberate engineering of the environment by human agency. Here, I presented a case study to illustrate this using the example of the 38-year-old case of state-wide terraforming semiarid landscapes in Ceará, Brazil. I tried to show that this process of terraformation is not only associated with the hydrographic infrastructure constructed throughout the decades, but also the construction of parliamentary democratic water governance system set up to regulate these relationships. Landscape terraforming can only be properly understood as a fundamental change in culture.

At the end of the Holocene, changes in mindset led to the Neolithic Revolution (Cauvin, 2000) [9] and there is evidence that mechanisms associated with how human societies run their economies prevail over adaptive factors. We must move beyond the view of history as natural experiments [21] and move to the social psychology of macroeconomic phenomena. If, as the present case study showed, we are consciously terraforming the planet (at multiple scales), then we cannot treat the reconfiguration of the Earth as a natural experiment. And this would be especially true at the local and regional levels of analysis. The findings of the present case study agree with Bierbaum et al. (2008) [34] that models focusing on adaptive capacities for sustainable development might be a dead end for designing effective environmental economic policies.

Two important points result from this. Firstly, the concept and case studies presented here on terraformation illustrate how the same process can have different interpretations, adaptive vs. constructivist (i.e., niche construction), depending on scale and degree of social consciousness. Secondly, future empirical research and the associated theoretical models that examine human-environmental relationships should put more emphasis on the impact of political decisions in the natural environment. Empirical studies, as the ones exemplified here, illustrate

In conclusion, terraforming should no longer be the stuff of science fiction but a serious field for understanding the details of how the natural environment is shaped by human will and action. We have learned the Tsembaga of Papua New Guinea, the Balinese of Badung, and the Cearenses of Northeast Brazil all engage in environmental economics that operate through different ritual regulations of their respective environments. Both the Balinese and the Cearenses terraform their environments, but only the latter did so by evolving a noösphere. This insight is key for understanding the role consciousness plays in shaping physical processes and should be the focus of studies seeking to explain very distinct processes of terraformation. However, the differences

between semiarid terraforming in Northeast Ceará vis-à-vis the Simbai and Jimi valley landscapes of New Guinea, or the irrigation water temple landscapes of Badung, Bali should not divert our attention from the fact that studying the environment as it is reconstructed by humanity will increasingly require the study of economic behavior from a political, cultural, and social perspective.

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