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Social Ecology as Critical, Transdisciplinary Science—Conceptualizing, Analyzing and Shaping Societal Relations to Nature

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Abstract: The sustainability discourse is, essentially, centered on the question of how complex relations between nature and society can be conceptualized, analyzed and shaped. In this paper, we present a specific interpretation of social ecology as an attempt to address this question. For this purpose, we establish Frankfurt Social Ecology (FSE) as a formal research program, which is based on the concept of societal relations to nature (SRN). The basic idea of the SRN concept is to put the modern distinction between nature and society at the start of a critical analysis. Such an analysis, we argue, has to focus on the interplay between what we call patterns and modes of regulation. Whereas patterns of regulation stand for the material and symbolic aspects of the organization of the individual and societal satisfaction of needs, modes of regulation mirror the norms and power structures of a society. Using an approach that is based on reformulating social-ecological systems as provisioning systems, we show how this interplay can be analyzed empirically. Finally, we propose critical transdisciplinarity as the research mode of choice of FSE. To conclude, we discuss how FSE can contribute to the development of a research program for a sustainable Anthropocene.

Keywords: Anthropocene; critical theory; social-ecological systems; social ecology; societal relations to nature; sustainable development; transdisciplinarity

1. Introduction

The implementation of the Sustainable Development Goals (SDG) by the United Nations as of 1 January 2016 is paradigmatic for two rather recent developments in science and in its relation to society. The SDG themselves have, on the one hand, re-emphasized the importance of research approaches, which enable an integrated perspective on global change and sustainability [1]. Such programs, like sustainability science, earth system analysis, human ecology or social ecology, have been around for quite some time now. They all try to answer the question of how we can conceptualize and analyze the complex relations between nature and society. On the other hand, the process of defining the SDG shows that the relations between science and society have fundamentally changed in the past three decades. Science today is expected to do more than pursue excellent basic research: It is supposed to align its research interests more closely with the knowledge demands of society [2]. In other words, science should contribute to both understanding and shaping sustainable relations between nature and society. Yet science is, in its current constitution, not only part of the solution; it is also part of the problem. As a functional system of society, science provides the means for the domination of nature and thus, ultimately, is one of the drivers that has turned mankind into a geological force, which now threatens to push the planet to its boundaries [3,4]. Moreover, the

disciplinarity that the science system still maintains and incentivizes prevents an understanding of the ways in which the very technology it helped create impacts the complex, interconnected systems we depend on [5].

The challenge for science that this brief description entails calls for nothing less than a research program for a sustainable Anthropocene (cf. [6,7]). Such a program is, presumably, still a long way off. Based on a cursory literature review as well as on our own experience in the field, we can, however, already name a few requirements such a program would have to fulfill. First, it would have to work on those theoretical problems that emerge in places where the relations between nature and society are perturbed in such a way that a sustainable development is blocked [8]. Second, it would have to be based on an integrative mode of research, which allows for the combination or synthesis of different theoretical or methodological approaches and various forms of knowledge [9]. Third, it would have to combine scientific research with societal practice, so that it could offer solutions for real-world problems and, at the same time, produce generalizable knowledge [10]. Finally, a research program for a sustainable Anthropocene would have to be (self)reflexive and (self)critical with respect to the double role of science as a provider of evidence and a driver of problems [11,12]. Against this background this paper introduces a particular interpretation of social ecology as developed by the Institute for Social-Ecological Research (ISOE) in Frankfurt (henceforth referred to as "Frankfurt Social Ecology" or FSE). Its aim is to show how these four requirements, in principle, can be integrated into the formal structure of a research program for a critical, transdisciplinary science.

1.1. Frankfurt Social Ecology in Historical Context

Social ecology as a field of scientific inquiry has a long and multifarious history (for an overview see, for example, [13]), which we cannot do justice to within the limited scope of this article. In order to put Frankfurt Social Ecology into context, however, we briefly refer to a few important antecedents and relationships here.

Social ecology today is, in the most basic terms, conceived as a scholarly approach, which starts off with the idea of separated material and constructed systems or dimensions and certain forms of transactions that mediate between the two [14]. On the epistemological level, this approach comes with a strong emphasis on the need to integrate scientific disciplines, theories and methods. In fact, the term "social ecology" was suggested by Milla A. Alihan [15] as the name of an analytical framework for studies of the relations between humans and their environments, which was intended to be more integrative than the field of human ecology as put forward by the Chicago School in the 1920s. This focus on integration is equally important for FSE.

In ways too widely ramified to be traced comprehensively here, the Chicago School is a key reference for contemporary human as well as social ecology. Founded mainly by the works of Robert E. Park, Ernest W. Burgess, Roderick D. McKenzie and Louis Wirth [15–17], the Chicago School set out to understand the principles of organization of the urban metropolis. Drawing on insights from plant ecology, the relations of human beings with their environments were described as the products of competition and selection [18]. The accepted development model was that of a cyclic change of states of balance and imbalance whereby community problems like social segregation, increasing crime rates, ethnic conflicts, or public health issues were interpreted as manifestations of the latter. The city was characterized as a "psychophysical mechanism", which possesses "a moral as well as a physical organization, and these two mutually interact in characteristic ways to mould and to modify one" [19] (p. 578). Although here it sounds like Park conceptualized the material environment as a distinct counterpart to the social aggregate, he (and most of his contemporaries) ultimately saw the city—drawing on the works of Charles Darwin—as a "web of life" [20] in which a distinction between what is natural and what is social is no longer possible.

There are two aspects of the Chicago School that are important for our discussion here: First, strongly influenced by American pragmatism, its scientific works were mainly aimed at providing the theoretical and methodological means to solve the real-world problems of contemporary societies [14].

Consequently, the proponents of the Chicago School were less concerned with laying out grand theories of the likes of Auguste Comte, Herbert Spencer or Charles Darwin, but with advancing interdisciplinary, empirical, and contextual research on community problems [21,22]. This pragmatic, problem-oriented approach has lived on in contemporary human and social ecology as it is represented by the College of Human Ecology at Cornell University, the School of Social Ecology at the University of California, Irvine and the Institute for Social Ecology at the University of Vermont, for example. As we will discuss in detail in Section 4, the problem-oriented approach is also a mainstay of FSE.

The second important aspect in the context of this paper is the use of the term "environment" in the tradition of the Chicago School. Even contemporary scholars [23] criticized that the term remained ambiguous in most papers written by Chicago School sociologists, in that it could both refer to the social and the extra-social environments of human beings. This ambiguity is still present in today's versions of social and human ecology, although more recent works routinely use the term so that it explicitly encompasses social and built environments, as well as natural ones [14]. Obviously, "environment" is a relative and definable concept. In order to avoid ambiguity, therefore, "environment" is not used in theoretical reflections in Frankfurt Social Ecology.

It is interesting to note that some important predecessors of the Chicago School, like Albion W. Small and George E. Vincent, already held this broader understanding of environment when they ascertained that "[s]ociety, in order to maintain its coherence and continue its development, must constantly readjust itself to natural and artificial conditions" and that, forestalling a systemic perspective, "[n]atural circumstances make an impression upon society, which in turn effects modification in nature" [24] (p. 336). For these forefathers of North American sociology, nature was a counterpart to society whereas in the organicistic approach of the Chicago School, nature was essentially conceived of as part of society [25].

The onward loss of nature as an analytical counterpart to society in North American sociology culminated in the structural functionalism of Talcott Parsons and was only redeemed with the rise to prominence of the New Ecological Paradigm (NEP) of Riley Dunlap and William R. Catton [26]. Although the programmatic stance of the NEP was to focus on the degradation of nature caused by the human appropriation of resources, it led to a "sociology of ecological problems" [27] in which the idea of interrelationships between nature and society took a backseat. In the following chapter, we will show that the distinction between nature and society, and a critical analysis of the relations between the two, is constitutive for our approach to social ecology.

In the German-speaking world, the development of social ecology is closely related to the discourse about the ecological crisis [28] and the formation of the corresponding political movements of the 1970s [29]. Part of this discourse was the critique that the then-pressing environmental problems were not adequately addressed by the established institutions and systems of knowledge production. In Germany, this has led to a differentiation of the science system. Until the end of 1970s, this system consisted of two sectors: the universities and the state-funded non-university research facilities. The foundation of institutes such as the ISOE by private, civil society initiatives lead to the formation of a third sector. These independent institutes pioneered the allocation of research capacities dedicated to dealing with concrete problems in the relations between nature and society. Unlike, for example, the Institute for Social Ecology at the University of Vermont, however, they conceived of themselves as being part of a scientific rather than a political movement. In Austria, the critique on traditional modes of knowledge production led to the foundation of dedicated departments within universities, most notably the Institute of Social Ecology at the Klagenfurt University (SEC). SEC's and FSE's interpretation of social ecology share the same overall approach to exploring the relations between nature and society but differ in important theoretical and conceptual details (for a comparison see Kramm et al., this issue).

1.2. Outline of the Article

The article is organized as follows: In Section 2, we introduce Frankfurt Social Ecology and her fundamental concept of societal relations to nature (in German "Gesellschaftliche Naturverhältnisse"). In Section 3, we show how a systems theory approach can help to make this concept productive for empirical research. At the center of this approach lies our model of social ecological systems as provisioning systems. In Section 4, we outline how FSE can be established as a critical, transdisciplinary science of societal relations to nature. Using the example of micro contaminants in municipal water cycles, we also demonstrate here how her main concepts can be applied in transdisciplinary research practice. To conclude the article, we briefly discuss a few open questions we consider to be important for the further development of a research program for a sustainable Anthropocene.

2. Frankfurt Social Ecology as a Research Program

Following Imre Lakatos (1970), we conceptualize Frankfurt Social Ecology as a research program. In his examination of Karl Popper's falsificationism, Lakatos characterized a scientific research program by its "hard core" [30] (p. 133). In terms of a methodological decision by the program's proponents, the hard core is conceived of as irrefutable. A "negative heuristic" is supposed to ensure that theoretical and empirical research avoids paths that would question the core's rationale. Instead, by means of articulating or inventing "auxiliary hypotheses", the program's proponents form a "protective belt" around the hard core and direct their research efforts at these ("positive heuristic"). Finally, a research program is successful if it leads to a "progressive problemshift", that is, if the program has "excess empirical content over its predecessor" and if "some of this excess empirical content is also corroborated" [30] (p. 113).

Lakatos developed his concept of research programs by reconstructing the history of the natural sciences in certain domains (mechanics and gravitation). Social ecology, in all its past and present diversity, however, cannot look back at a long sequence of attempts to advance the understanding of a shared and precisely defined object of research. Lakatos' concept thus cannot be transferred straightforwardly to social ecology. Yet, in an ex-ante manner, its basic structural ideas can serve as formative principles for a science in statu nascendi. This is how Frankfurt Social Ecology came about as an open, continuously evolving research program over the past 30 years at ISOE. Its core ideas became the basis of a dedicated, still ongoing research funding initiative by the German Federal Ministry for Education and Research [31].

An important prerequisite for this development was, and still is, the existence of a specified hard core. Generally, the hard core can effectively serve as a guarantor for stability and identity over time, so that a productive scientific community can develop around a research program in the first place. In the case of FSE, the concept of societal relations to nature serves that purpose. Obviously, SRN, as much as any other hard core, did not come into existence fully fledged. It emerges rather in the course of an ongoing "process of trial and error" [30]—a process which is driven by, for example, changes in the scientific or societal contexts of the program. Reflexivity and critical faculty are key to shaping this process so that the program can develop progressively. What Lakatos' analysis also teaches us is that a successful research program has to provide a clear, workable link between the theoretical reflection on and the practice of empirical inquiry into its subject matter. (In Section 4 we will show how this link is realized in Frankfurt Social Ecology.) Moreover, we consider the notion of a positive heuristic to be prolific: It should consist of procedures for identifying constructive research questions and hypotheses, help structure research processes, and provide guidance for the treatment of research problems.

Before we define the SRN concept and show how it helps to form FSE as a research program, we note that Frankfurt Social Ecology differs in another crucial aspect from the sciences Lakatos discussed: FSE positions herself in an explicitly normative context, which consists of two related components: First, FSE assumes that the current global relations between nature and society are fundamentally perturbed—a diagnosis of the time that is of course well known under various terms such as "ecologic crisis" [28], "non-sustainable development" [32] or, in some interpretations, the Anthropocene [4].

We refer to this normative component as the crisis of societal relations to nature. Second, social-ecology is a problem-oriented research program. That is, it aims at empowering societies in dealing with historically and geographically specific manifestations of this crisis. For a research program that adheres to the scientific method, it is crucial to separate such normative components from the purely descriptive ones [33]. In Frankfurt Social Ecology this operation is explicitly defined as a self-critical and self-reflexive task [34].

2.1. Societal Relations to Nature

The hard core of Frankfurt Social Ecology as a research program is the concept of "societal relations to nature". We define the term to represent the relations between nature and society in their historical development [35]. Our definition includes three postulates: First, nature and society are different things. Second, although distinct, nature and society cannot be treated as being independent from one another. Third, relations between nature and society are given as characteristic, observable patterns, which, in any given location, might transform over time. We refer to such patterns as "patterns of regulation". They have both material and symbolic attributes. While the latter, in the most general terms, refer to flows of information and meanings, the former account for flows of matter and energy. In the following, we will discuss these postulates and their implications for establishing FSE as a research program in more detail. We note that our definition of SRN does not contain any implicit normativity.

With the first postulate, Frankfurt Social Ecology takes a Western, essentially Cartesian, cultural tradition as its point of departure. At its core, this tradition is about the question of what can be associated with human action and decision-making and what cannot. In most general terms, the answer is that there is a universal nature and a contingent culture [36]. This tradition is still highly influential, as the current discourse about the Anthropocene demonstrates. Here, it is about nothing less than a redefinition of what it means to be human in relation to an outside natural world, which is thought to be manageable [37]. The achievements of this tradition are well known. They culminate in what has been termed modernity. Equally well known are, however, its ramifications on the social, ecological, political and scientific levels. Frankfurt Social Ecology is set up as a critique of this dualistic tradition. This manifests itself in a scientific procedure we call "double-sided critique". Double-sided critique can be understood as a functional equivalent of dialectics and aims at scrutinizing binary oppositions such as realism/constructivism, male/female, subject/object etc. as powerful social constructs on the levels of both societal and scientific practice. As far as the latter is concerned, such practices materialize in the "Great Divide" [38] between the natural sciences, on one side, and the social sciences and humanities, on the other. (This divide is synonymous with a methodological rather than ontological distinction between nature and society [35].) Double-sided critique plays the role of the negative heuristic in the research program: It should help to avoid lines of research that reproduce analytical dualisms [9]. Conversely, this implies that FSE has to establish herself as an integrative research program. In Section 4, we will, therefore, introduce transdisciplinarity as the research mode of choice of Frankfurt Social Ecology.

The distinction between nature and society is historically, geographically and culturally variable [37]. What counts as "natural" or "social" in any given context depends, among other things, on power and gender relations, institutional arrangements, political-economic regimes as well as on the type and availability of resources for the satisfaction of individual and social needs. The first postulate thus also implies that FSE has to examine cultural practices of distinction empirically and, in so doing, make the social orders that underlie such practices accessible for critical analysis. This line of research is part of the positive heuristic of Frankfurt Social Ecology. We note that the resilience approach as put forward by the Resilience Alliance sees the delineation between natural and social systems as arbitrary and conceives humans as parts of the ecosystem [33,39]. From the perspective of FSE, this risks ignoring the real-world effects of prevailing practices of distinction.

The second postulate refers to something that has strongly influenced the development of the sciences during the 20th century and that scholars like Ernst Cassirer, Alfred N. Whitehead or Gregory Bateson reflected upon philosophically in their works: the concentration of the epistemological interest on relations instead of things with specific intrinsic features and thus on functions instead of substances and on processes instead of structures [40]. What it means epistemologically and ontologically, however, to analyze relations is a non-trivial and still open question [40]. In the following chapter, we will, therefore, in a pragmatic approach, use the concept of social-ecological systems to make SRN accessible for empirical research.

Moreover, it is possible that directing research towards practices of distinction generates or reproduces dualisms and, therefore, thwarts the identification of relations or, as Brandom notes, "[a] distinction becomes a dualism when its components are distinguished in terms that makes their characteristic relations to one another ultimately unintelligible." [41] (p. 615). It is important to keep in mind here, however, that a conceptual distinction and the social appraisal of that which has been distinguished are not the same things. In other words, a distinction itself does not necessarily imply a revaluation or devaluation of either side; this only happens in the societal context in which the distinction is made. FSE, therefore, needs explicit and precise procedures for making distinctions. Moreover, FSE does not stop at analyzing existing binary distinctions and their effects when dealing with, for example, community problems. She also tries to identify new relations within the established dualisms. Consequently, FSE has to conceptualize the operations of making distinctions and identifying relations as two phases of a formal cognitive process. In Section 4 we will show how such a process can be organized in research practice.

The third postulate introduces the term "patterns of regulation". This establishes, on the one hand, the basic hypothesis that the relations between nature and society are always given in (self)organized forms. On the other hand, in using the term "regulation", we refer to corresponding theoretical approaches for understanding the principles that govern such forms (like, for example, second order cybernetics [42]). In the following section, we will take a closer look at these two aspects. Yet no matter how regulation is treated theoretically, the third postulate implies that FSE has to provide a procedure for distinguishing between the patterns' symbolic and material attributes. Although most approaches for understanding and analyzing nature-society-interactions make this fundamental distinction [8,14,39,43,44], to our knowledge, such a procedure is currently not available. At this point, therefore, we can only indicate a rather coarse approach. It is based on characterizing material relations by their causal effects and symbolic ones by their meanings for an observer [40].

So far, with the SRN concept, Frankfurt Social Ecology appears to only operate on the macro level of society—an objection, which is also brought forward against systems theory approaches in the field [45]. In fact, by putting the distinction between nature and society first, and not that between the human and the non-human, she initially ignores many aspects, which, for example, anthropology, economics, sociology or psychology examine extensively. In the following section, we describe how FSE conceptualizes the relations between the individual, society and nature in more detail. The basic approach is to relate SRN, at the most fundamental level, to the processes of satisfying basic human needs such as food, shelter and reproduction (in this context, we also use the term "basal societal relations to nature" or, in German, "basale gesellschaftliche Naturverhältnisse"; [46]); yet these processes always exist, for the socialized individual, only in culturally and thus socially interpreted forms. Besides the use of the concept of (basic) human needs [47], FSE also applies concepts such as "everyday routines" [48] and "social practices" [49,50] in order to make the individual actor perspective accessible for theoretical and empirical research. Moreover, FSE reflects gender/sexual reproduction as a primary pattern of social order. A basic assumption is that SRN are strongly structured by gender relations and vice versa [51].

In the previous section we introduced Lakatos' idea of a protective belt, which shields the hard core of a research program. In Frankfurt Social Ecology the protective belt is realized as a network of higher order concepts, which all refer either directly or indirectly to SRN. Regulation, as introduced

above, is an example of such a higher order concept. Others are the concept of social-ecological systems as a means of analyzing SRN empirically (see the following chapter) as well as the concepts of human needs, everyday routines and gender/sexual reproduction. The higher order concepts and their links among each other or with SRN are the results of generalizations in the outcomes of contextual or problem-oriented empirical research. They form, together with any specific theory they might be associated with, the theoretical knowledge of FSE. Reformulating existing higher order concepts or adding new ones to the protective belt is part of the ongoing development of Frankfurt Social Ecology.

2.2. Regulation and Transformation of Societal Relations to Nature

Societies have to shape their relations to nature in order to sustain the process of life intra- and inter-generationally. If a society fails in this effort, it collapses [52]. In this sense, the patterns of regulation introduced above can be interpreted as preconditions for viable social orders. When societies' interactions with nature become dysfunctional (for example as a result of the overexploitation of natural resources or the failure of a mechanism for their cost-efficient provision), they react by regulating the corresponding patterns of regulation. In any society, however, the ways in which such second order regulations can be realized are constrained by what we call "modes of regulation". They mirror the power relations, cultural norms and conflicts of interest in a society and thus represent "social relations" [53,54]. With respect to the terminology introduced above, this means: Whereas patterns of regulation always have both material and symbolic attributes, modes of regulation only have symbolic ones. A key scientific problem of Frankfurt Social Ecology is to understand the interplay of these two levels of regulation in order to identify or anticipate looming crises of SRN. We note that with this approach it becomes possible to analyze local crises of SRN in an overarching societal context such as capitalist modes of production.

What this approach does not specify is, however, on which level of social aggregation patterns and modes of regulation are located. They emerge from both the interactions between individuals and the interplay of institutions or fully differentiated functional systems. Consequently, understanding crises of SRN requires analyzing not only complex interactions on various spatial and temporal scales, but also on social ones (cf. [46,55]):

- On the micro level of individual actions, patterns of regulation are tightly knit to the corporeality of humans and psycho-physical processes—for example to feelings of deprivation, ways of perception and ideas of identity. This level thus primarily addresses the forms of satisfaction of individual needs. These forms are expressed by, and dependent on, practices and routines of everyday life as well as on the norms and power structures that are associated with various modes of regulation on higher social levels.
- On the meso level of organizations and institutions, patterns of regulation essentially address the collective needs of society. They materialize as provisioning systems, for example, for water, food and energy, or as techno-structures, like those for mobility and communication. The forms of needs satisfaction on this level depend on the availability of vital goods and services as well as access to, and the usability of, the techno-structures. They are shaped by certain modes of regulation such as property relations.
- On the macro level of society powerful modes of regulation like, for example, relations of production, property and gender provide the contexts and dispositifs for the processes of needs satisfaction on the lower levels of social aggregation. They take the form of political-economic regimes and thus define the limits within which SRN can be regulated on the meso and micro levels.

Ideally, the patterns and modes of regulation interact in ways so that social integration succeeds and societal reproduction is continuable in the long run. Such a condition is, on a descriptive level, analogous to resilience in a social-ecological system [39]. Problems with this interplay occur when the available options for second order regulations are insufficient to counter an unfolding crisis of SRN.

In a historical perspective, such problems lead to fundamental changes of the patterns and modes of regulation. We refer to such changes commonly as "transformations". Conceptually, "transformation" denotes a process, which leads from an initial pattern or mode of regulation to a new one with respect to a given context of regulation. In such a process the relations that define a pattern or mode can become rearranged, broken up or replaced entirely (the implementation of centralized water supply systems in Europe at the end of the 19th century and the rather recent debate about the privatization of water services can serve as examples of transformations of patterns and modes of regulations, respectively). Transformation, in Frankfurt Social Ecology, is a higher order concept and thus part of the protective belt of the research program.

Subjects of transformations are natural phenomena and all actors, individual or collective, whose actions or behaviors influence the form or stability of a given pattern of regulation. Transformations can, therefore, have both intentional and unintentional drivers. Frankfurt Social Ecology uses the concept of transformation in a descriptive manner. The historiographic description of moving from one pattern of regulation to another is the basis for analyzing those factors that have, or will have, determined starting point, course and endpoint of a transformation. For such an analysis, various theoretical avenues can be followed. FSE focuses on those that address power relations, like hegemonic or regulation school theories [56–58], gender relations [59,60], or the diffusion of technological or social innovations [61,62]. The aim of the analysis of transformation processes is to discern or anticipate critical changes in the relations between nature and society as well as to identify those levers for interventions that help steer the course of a transformation in a desired direction—an analytical perspective, which is also emphasized in resilience-based studies of social-ecological systems [63,64].

Whereas there has been progress in creating sustainable patterns and modes of regulation on the local and regional levels in the past few decades, those on the global level are undoubtedly non-sustainable. The familiar keywords are here: climate change, social inequality, loss of biodiversity, poverty or land degradation. Frankfurt Social Ecology starts from the assumption that sustainable development becomes possible only when both the corresponding patterns as well as the modes of regulation are changed. We refer to such intentional processes of change towards sustainability as "social-ecological transformations". In FSE, this term, therefore, is used in a normative manner. The definition, passage and implementation of the SDG can be interpreted as the attempt to initiate such social-ecological transformations. The prevailing critique of the SDG that they lack an integrative perspective and that, therefore, goal conflicts are likely [1,65,66], means, in our terminology: The interplay between the patterns and modes of regulation that the various SDG address were not sufficiently taken into account.

3. A Systems Approach to Social Ecology

In the previous chapter, we suggested that SRN cannot be analyzed empirically as such. One way to make them proper objects of empirical research is to represent SRN as social-ecological systems (SES). In this chapter, we examine this idea more closely. Drawing on general systems theory, we define a system as "a set of objects together with relationships between the objects and their attributes" [67] (p. 18). An SES-based approach is common in most elaborated frameworks for the (problem-oriented) analysis of the interactions between nature and society (for a comparative overview see, for example, [45]). Although these frameworks differ in general layout, theoretical underpinnings and conceptual details, there appears to be a consensus on how to define and analyze SES. It can be characterized by three core ideas [8,39,43,68–71]: First, SES are a conjunction of anthropocentric (social aspects in an ecological context) and ecocentric (natural aspects in a social context) perspectives; second SES are complex, adaptive systems, which operate on interacting and hierarchically structured spatial, temporal and social scales; third, analyzing SES requires an interdisciplinary, theoretical framework.

Frankfurt Social Ecology adopts this understanding of SES [72] but adds two more key characteristics: First, SES are not real objects, but models of knowledge about real-world phenomena—they are, in other words, "abstract objects in an ideal world" [73]. In the sense of the rationale

introduced in the previous chapter, SES are being constructed by relating the results of scientific or societal practices of distinction between nature and society. The historical contingency of such distinctions is, therefore, as much part of the systems as is the interpretation of the modelled reality by those who construct the model or by those who are represented as actors within it. This leads us to the second characteristic of SES that Frankfurt Social Ecology adds to the consensus outlined above: Science itself is an actor of the SES it sets out to analyze, that is, science is a participant observer. SES are, therefore, self-describing and self-referential systems—an aspect that, so far, has received little attention in the pertinent literature [74].

Generating generalized knowledge about its object of interest is a core aspiration of any research program. Because of their formal structure, systems theory approaches seem to be an ideal means towards that end. From what has been outlined up to this point, however, it becomes clear that SES in Frankfurt Social Ecology cannot claim the status of universally valid descriptions of the dynamic relations between nature and society. Rather, SES are always historically and geographically specific representations of such relations, that is, SES can be conceived of as problem-specific social-ecological case studies. Producing generalizable knowledge in FSE, therefore, either requires observing a given case in its temporal development or working out factual analogies to related cases [10]. We return to this in the following chapter.

Social-Ecological Systems as Provisioning Systems

Significant progress in modelling techniques like, for example, agent-based modelling [75] notwithstanding, SES have, as yet, had mostly a heuristic function in research approaches for the analysis of human-nature-interactions [33]. Realizing SES as analytical models requires considerable, strongly structuring simplifications. As a first step toward that end, Frankfurt Social Ecology conceptualizes SES as provisioning systems [76,77]. The term "provisioning", in our definition, includes any benefit societies draw from natural resources. More specifically, and terminological ambiguity notwithstanding, it spans all four ecosystem service categories of the Millennium Ecosystem Assessment, that is: supporting, provisioning, regulating and cultural services [78]. In addition, our understanding of "provisioning" involves forms of care work and, therefore, connects to the feminist discourses about, for example, the crisis of reproductive work [76,79].

Conceptualizing a concrete social-ecological system as a provisioning system means, essentially, to realize it as a specific arrangement of patterns and modes of regulation. Figure 1 shows the basic components of SES as provisioning systems. Via the utilization of resources, provisioning systems connect natural objects, like rivers, forests and oceans, to the societal realms of action and decision-making. The process of resource utilization in provisioning systems is, however, not represented by direct links between users and resources, but rather by four contextual factors: practices, knowledge, technologies and institutions. These four factors are, in a nutshell, the building blocks of the patterns and modes of regulation the system is supposed to model. Such a provisioning system can thus be interpreted as representing characteristic SRN. We note that our model of social-ecological systems as provisioning systems has considerable similarities to Elinor Ostrom's social-ecological systems framework [71]. Her framework particularly emphasizes the role of governance and institutions for resource utilization and management.

Basically, we designed our model of SES as provisioning systems to be scale independent. This means that the analysis is neither limited to certain spatial and temporal scales nor to the macro level of society. The depth in which the social and ecological components of the system are described rather depends on the given research problem and, therefore, on the specific constellation of the transdisciplinary research process (see next chapter). In more concrete terms: How and with which variables the components "resources" and "users" as well as the four factors are described, is the result of a learning process among the scientific and, where applicable, the non-scientific actors participating in the research process. Various research projects at ISOE have demonstrated that the translation of the relatively few elements and premises of the model into variables for empirical research is rather

straightforward [76,80–82]. As a formal method for realizing SES as provisioning systems, Bayesian belief networks have proven successful [83]. Cross-scale analysis is the crux of the matter of any SES study. As already indicated above, hierarchical approaches to scale are particularly appropriate for FSE because they emphasize the fact that "the observer is critical to defining scale" [84] (p. 782). As Allen and colleagues also note with respect to the panarchy concept [85], however, applying such approaches in empirical research is still in its infancy in FSE.

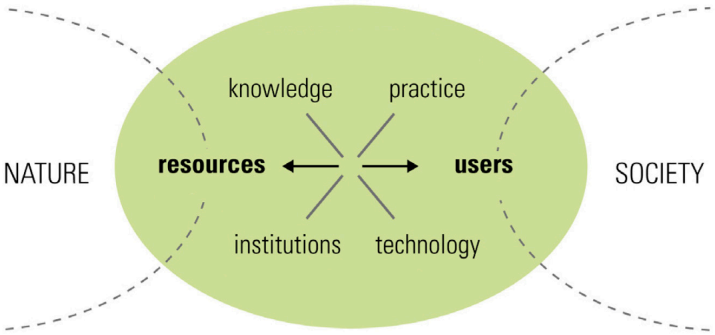

Figure 1. Social-ecological systems as provisioning systems (modified according to [76,80]). Note that the green ellipse represents already the social-ecological system. The two dashed ellipses simply indicate the environment of the constructed system. This environment consists of natural and societal aspects that are not part of the system, but can nevertheless have a (significant) impact on it.

4. Frankfurt Social Ecology as Critical, Transdisciplinary Science

On the scientific level, Frankfurt Social Ecology aims at a critical analysis of the complex relations between nature and society. In reference to the normative context introduced above, FSE also aims at contributing to shaping these relations in a sustainable way. Inferring from what we discussed so far, the combination of both goals requires a mode of research, which fulfills three requirements: First, it has to be open to theoretical and epistemological pluralism; second, it has to provide a strong link between theoretical reflection and the empirical analysis of real-world problems; third, it has to think practice within theory, that is, it has to reflect upon the implications of science as a functional system within society. A research mode that fulfills all three requirements is critical transdisciplinarity [34,86–89].

The discourse about transdisciplinarity has a long and eclectic history that we cannot reproduce within the limited scope of this article (for a synopsis see [86]). For our purpose here, we thus define transdisciplinarity as being "a critical and self-reflexive research approach that relates societal with scientific problems; it produces new knowledge by integrating different scientific and extra-scientific insights; its aim is to contribute to both societal and scientific progress; integration is the cognitive operation of establishing a novel, hitherto non-existent connection between the distinct epistemic, social–organizational and communicative entities that make up the given problem context" [86] (p. 8f). (Note that this definition of transdisciplinarity implies that, usually, non-scientific actors participate in the research process.) The first requirement is implicit in this definition. The second can be met with a formal procedure we will introduce in the following section.

For the third requirement, we draw on elements of the critical theory of the Frankfurt School [90]. An essential feature of critical transdisciplinarity is thus to analyze the functions and status of science and scientific knowledge production within society as well as their role in preserving the current (non-sustainable) state of affairs. From this point of view, science and, for that matter, scientific theories cannot be conceived of as independent from the other branches of production in capitalist societies. A critical theory of society lays bare the ways in which theories that encapsulate knowledge for the domination of nature reflect the social context in which they were developed. For an in-depth discussion of the relation between critical theory, transdisciplinarity and social ecology see, for example, [35].

Linking Theory and Empirical Research Practice in Frankfurt Social Ecology

Linking theory and practice in Frankfurt Social Ecology requires relating the SRN concept to transdisciplinary research. The basic approach here is to provide a procedure, which translates historically and geographically unique realms of the relations between nature and society into "epistemic objects" [91,92]. In the following, we present the four basic steps of such a procedure.

We call the starting point of transdisciplinary research a "case". A case consists of an issue and a problem. An issue is a proposition, which conveys the approved state of scientific knowledge with respect to the chosen realm of reality. An example of an issue is the phrase "Active pharmaceutical ingredients are found in water bodies with concentrations in the range of X to Y µg/L". As "problem", we define a statement, which refers to an issue in an evaluative manner. Here, the reference can be implicit or explicit, conscious or unconscious. "Active pharmaceutical ingredients pose a risk for aquatic ecosystems and public health" is an example of such a statement. It is crucial to note here that, generally, such an assessment is made under scientific uncertainty. It is not (entirely) objective but guided by norms, values, or interests. It is precisely for this reason that transdisciplinarity strives for a shared problem description among all actors involved in the research process [86].

Turning a case into an epistemic object now means applying certain formal operations [46]. Figure 2 shows four such operations: distinguish, relate, assess and arrange. Being part of social ecology's protective belt, they are the basic operations with which patterns of relations between nature and society can be identified and made scientifically accessible. The links between the four operations, as shown in Figure 2, describe a four-step process, which takes place at the beginning of the transdisciplinary research process. The first step is to distinguish between the natural and the social attributes of the given case. The guiding question here is: "Which distinctions can be stated that do not contain implicit or hidden assumptions about relations between the distinguished attributes?" Attributes, for which this turns out to be impossible, are called "hybrids" [74]. In such hybrids, a relation between natural and societal entities is, in a manner of speaking, historically embedded. A rectified section of a river is, in this understanding, a hybrid. Hybrids demand particular attention during the ongoing research process as they might need to be disentangled in order to move towards a solution to the problem associated with the given case.

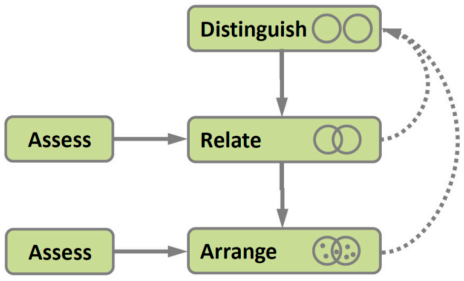

Figure 2. The general procedure for translating SRN into epistemic objects for empirical research by means of four formal operations. The dotted arrows indicate that the respective operations have to be applied iteratively. The circles symbolize the domains of nature and society.

In the second step researchers identify or establish relations between the differentiated attributes. The guiding question for this task is: "Which social structures and processes connect those attributes of the given case that were previously classified as 'natural' or 'social'?" Or, in other words: "Which relations can be regarded as characteristic in the sense that they represent a culturally embedded relation between nature and society?" Within the pattern of relations emerging from this second step, researchers then distinguish between material and symbolic relations (the repeated application of the formal operation "distinguish" is represented in Figure 2 by the upper dashed arrow). As we demonstrate in the example (see Table 1), the differentiation between "material" and "symbolic" is neither trivial nor always unambiguously possible.

Table 1. Application of the four basic formal operations of FSE to the case of active pharmaceutical ingredients (API) in water bodies (see text for explanations).

A four-step process for translating SRN into epistemic objects of research
The case can be described as follows: Active ingredients of pharmaceuticals for human use (API) are being increasingly observed in municipal water cycles. Little is known, however, about the adverse effects on wildlife and humans at measured concentrations. Correspondingly, effective measures for reducing APIs in water are lacking. Note that this and the following descriptions are not intended to be exhaustive or to represent the current state of knowledge of the case. They have been strongly simplified to provide a concise example (for more detailed information on this case see [93]).
Step 1—Distinguish
Applying the first formal operation can lead to the following description: Natural attributes of the case are aquatic ecosystems and groundwater reservoirs; social attributes are public health, individual needs for physical and mental health, and providing the population with clean drinking water; hybrids are humans, here in their roles as patients and consumers of drinking water.
Step 2—Relate
The attributes distinguished above are connected by a web of relations, which we cannot reproduce in full in this example. The basic relation is established by the functionality of pharmaceuticals: APIs are not fully metabolized by the human body so that a certain fraction of an ingested dose is excreted and ends up in domestic sewage; when these APIs survive sewage treatment, they might reach rivers where they are taken up by aquatic organisms, get deposited in sediments and infiltrate aquifers; if they eventually break through the systems of water purification, they return to humans in the form of contaminated drinking water.
The material side of this specific SRN is characterized by flows of matter (substances). The symbolic side includes technical and institutional arrangements in the healthcare and water supply systems, culturally imparted ideas of physical and mental health with respect to both the purposeful application of drugs as well as the unintended uptake of APIs via contaminated drinking water, personal hygiene, water as the most fundamental life-sustaining natural resource and corresponding notions of purity, and healthy aquatic ecosystems as sources of food and recreation.
Note that the distinction between material and symbolic attributes of the identified relation does not necessarily follow the one between natural and social. If a society, for example, values healthy aquatic ecosystems (symbolic relation), then the definition of what counts as "healthy" is largely independent from the actual concentrations of APIs in water bodies (material relation). Rather, it is the result of societal negotiation processes about safety limits.
Step 3—Assess
Drawing on the state of scientific knowledge, the identified relation can be assessed as follows: water cannot be free from contaminants; water purity is always related to the level of pollution and the available measurement accuracy; for a number of reasons, the validity of current risk assessments for APIs in water is principally limited; the chemical properties of most drugs make their partial excretion and slow degradation in the environment unavoidable; environmental engineering today provides no single technology which completely eliminates all APIs from domestic sewage or sources of drinking water; prevailing practices of the prescription, use and disposal of drugs are deeply rooted in ideals and norms of physical or mental fitness and certain lifestyles.
From this description of the case's issue it follows that the corresponding societal problem can neither be reduced to fit the approach of the natural or engineering sciences (for example, in terms of the toxicological assessment of environment and public health hazards by the occurrence of APIs in water, the definition of corresponding safety limits, and the removal of drug residues from municipal sewage by advanced treatment technologies) nor to that of the social sciences (for example, the deliberation of environment and public health risks or the promotion of behavioral change in the handling of pharmaceuticals to keep APIs out of municipal water cycles). The argument of this second assessment (double-sided critique, here greatly abbreviated) is that, as it turns out, the normal mode of operation of the health care system inadvertently causes the occurrence of APIs in municipal water cycles.
The societal problem of the case that can be derived from this description can thus be defined as follows: What are efficient strategies for reducing the occurrence of APIs in water that do not impair the quality of health care? Note that this description can already serve as the epistemic object of research.

Table 1. *Cont.*

A four-step process for translating SRN into epistemic objects of research
Step 4—Arrange
It is now possible to represent the identified relations as a social-ecological system by applying the fourth formal operation. For this step it is first necessary to single out the patterns and modes of regulation that are deemed most relevant in addressing the identified problem. Important patterns of regulation are the development and production of pharmaceuticals, their description and (gender-specific) use for the prevention and cure of diseases as organized by the healthcare system, and the systems of municipal sewage disposal and water supply. Key modes of regulation are prevalent norms regarding physical and mental fitness as well as policies with respect to drug authorization and environmental protection.
An analysis of the interplay between these patterns and modes of regulation shows that, for example, under current European law, it is not possible to deny authorization of a new drug even when it demonstrably poses a risk for the environment. Moreover, it turns out that, as a rule, safeguarding the quality of healthcare outweighs environmental protection as far as the public opinion is concerned. From the assessment in the step 3 it clearly follows that these critical interplays need to be addressed in order to find sustainable solutions for the identified problem. Once this analysis for relevance is completed, the remaining set of patterns and modes of regulation can be arranged to represent a social-ecological provisioning system (see Section 3 for further explanations).

The third formal operation requires assessing the established relations. It consists of two parts: For the first part, the guiding question is: "How do the identified relations reflect the current state of scientific knowledge and to what extent do they represent the case or (justifiably) go beyond it?" (In the latter case the description of the case might have to be revised or extended). Note that from this part the specification of the issue of the given case results. For the second part, researchers apply what we above called "double-sided critique". The guiding question here is: "To what extent are both the analytical distinctions between 'natural' and 'social' as well as those between 'material' and 'symbolic' dependent on the disciplinary or epistemological backgrounds against which they were made?" Those attributes that were characterized as hybrids in the first step deserve special attention in this assessment. They have to be assessed as to which social practices of distinction are inscribed in them as well as to whether, as a unit, they represent, or rather cover, the given problem. If applicable, it might become necessary to disentangle the hybrids so that their embedded relations between natural and social attributes can be critically analyzed. As a consequence of the assessment step it might become necessary to repeat steps one to three (indicated in the figure by the lower dashed arrow). An important result of step three is the description of the societal problem that is associated with the case at hand. In transdisciplinarity, it is determined jointly by the researchers and the participating societal actors [86].

In the final step, researchers arrange the identified attributes and their relations. According to the systemic approach of FSE, the guiding question here is: "Is it possible to describe the identified composition as a provisioning system?" In case this turns out to be possible and expedient, this formal operation amounts to arranging the identified relations between the natural and social attributes in a way that singles out those which are considered important for understanding and solving the given problem. The system, thus defined, is being assessed according to the procedure introduced above (as a result, it might become necessary to rerun the entire process). The social-ecological system that finally emerges from this last step is the epistemic object of research.

It is important to keep in mind here that such an epistemic object only exists temporarily, that is, it might become modified in the course of the transdisciplinary research process. The reason is that identifying a pattern is observer-dependent [84]. Since the perspectives of observers, that is scientists and non-scientific actors, change during the process, something that appeared to be a pattern in the first place, might change its form or even dissolve entirely. It is an essential aspect of good research practice in Frankfurt Social Ecology to deal with the possible instability of the epistemic object and thus of the reference to the initial problem.

Note that the system knowledge produced in transdisciplinary research on social-ecological cases is context-specific initially; it forms the basis for developing orientation and transformation knowledge for dealing with critical developments in the examined SRN [86]. The ultimate scientific goal of the research is to decontextualize or generalize the case knowledge produced. As we already mentioned in the previous chapter, the approach here is to observe a particular case in its historical development (each transdisciplinary research project on a particular case can be viewed as a data point on a timeline) or to carve out factual relations to other cases (Figure 3). Connecting case studies this way leads to new higher order concepts (see Section 2.1) and augments or even entirely discards, existing ones. This changes and strengthens the protective belt of the research program and thus broadens the theoretical knowledge of social ecology. Formalizing and operationalizing the process of moving from case study results to generalized knowledge is an important and still unsolved issue in this context. Experiences and data, such as those gathered by the Long-Term Socio-Ecological Research (LTSER) platforms (cf. [94]), can particularly help to advance it.

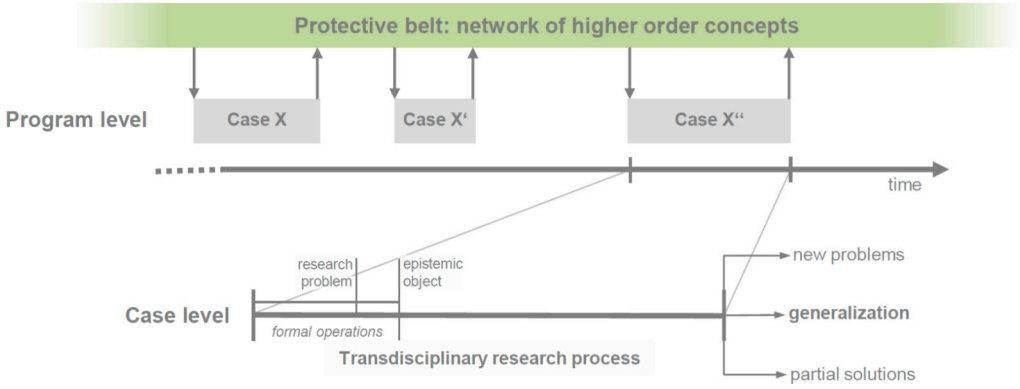

Figure 3. The connection between the production of case knowledge and theoretical knowledge in Frankfurt Social Ecology. The light gray rectangles each represent a complete transdisciplinary research project on a given case. The down-arrows indicate that, for defining the problem at the beginning of the research process, the theoretical knowledge of social ecology is used. The up-arrows symbolize the decontextualization and generalization of the case knowledge at the end of the project.

5. Conclusions

In this paper, we established Frankfurt Social Ecology as a critical, transdisciplinary scientific research program for studies of societal relations to nature. The aim of the program is to understand these relations and to contribute towards shaping them in a sustainable way. We have argued that a key scientific problem of FSE is to analyze the interplay of patterns and modes of regulation in order to identify or anticipate looming crises of SRN. Whereas patterns of regulation stand for the material and symbolic aspects of the organization of the individual and social satisfaction of needs, modes of regulation mirror the norms and power structures of a society. We introduced the conceptual model of social-ecological systems of provision and showed how it helps to make SRN accessible for empirical research. Finally, we argued that critical transdisciplinarity has to be the research mode of choice of social ecology. This mode, on the one hand, provides the framework that links the production of new scientific knowledge with the development of (partial) solutions for concrete societal problems. In so doing, it forms the basis for the continuous development of FSE as a scientific research program. On the other hand, drawing on critical theory, critical transdisciplinarity allows for a reflection of the social contexts of scientific knowledge production.

We note that, although critical theory was, and is, a key reference for the development of Frankfurt Social Ecology, its precise interpretation for the program has, so far, not been clarified conclusively. Yet such a clarification is necessary in order to avoid upholding old mistakes and misconceptions, which have been identified as being intrinsic to critical theory [95]. An approach we currently pursue here is to re-examine the seminal texts on critical theory in order to identify those elements of the theory that are prevailing and adaptable to the basic rationale of social ecology. An important outcome of this endeavor would have to be a theory, which sheds light on how the relations between science and society have changed in the Anthropocene and on what this change implies for the established institutions and procedures of democratically legitimized decision-making—issues that are also discussed in the context of transdisciplinarity, albeit, so far, inconclusively [96,97].

In the introduction we argued for the need of a research program for a sustainable Anthropocene. Our aim here was to show that Frankfurt Social Ecology, along with her founding principles and concepts, could serve as a first step towards such a program. There are, however, problems, which need to be addressed in order to continue on this path. We highlight two of them here: First, FSE and, for that matter, a research program for a sustainable Anthropocene would benefit from a thorough justification for the need of a systems theory approach. An examination of the neo-cybernetic concept of "second order observations" [98] or "observing systems" [99], in our view, has the potential to

provide a sound methodological foundation for such a justification. Second, there is currently no compelling social theory, which could explain the development of the epochal crisis of SRN as it manifests itself in the Anthropocene concept. Given the essence of our subject, such a theory cannot spring from a purely sociological endeavor but only from an interdisciplinary one. It would, on the one hand, have to provide the means to describe how SRN form as a result of the satisfaction of (basic) human needs. On the other hand, it would have to posit society as already existing and then help to explain how its structures and processes frame the formation of SRN in the first place. The concepts of patterns and modes of regulation presented here can be interpreted as a pragmatic makeshift for such a social theory.

We established Frankfurt Social Ecology as a critique on the dualistic mindset of modernity. Unlike more recent approaches in, for example, anthropology, however, social ecology does not aim at "understanding the world without dissociating the symbolic from the material" [100]. Instead, FSE tries to make practices of distinction between such binary oppositions and their real-world consequences accessible for critical analysis so that new, more sustainable relations can be established. Nevertheless, we believe a mature research program for a sustainable Anthropocene would eventually have to discuss coexistent, non-Western ontologies [36] and their corresponding epistemologies more thoroughly in order to map the road towards a sustainable future for humanity.

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Conflicts of Interest: The authors declare no conflict of interest.

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