Chapter 2
Core Concepts and Heuristics

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Abstract This chapter outlines the basics of our socioecological theory. It starts with the question of why entities such as 'culture' have been so successful that an evolving species like humankind could become the dominant power on the planet. It explains social systems as 'hybrids', a structural coupling between a (cultural) communication system and interconnected biophysical elements. In what sense are humans, domestic animals and artifacts hybrids? In what sense do these elements 'belong' to a certain cultural (communication) system? The constitutive operation is 'colonization'. Human beings are culturally 'colonized', as are their livestock and their artifacts. These hybrid elements and the metabolic flows required to maintain them determine the social system's impact upon the 'rest of nature'. This influence happens through the metabolic exchange of energy and materials (which in part occurs unintentionally, such as breathing or evaporation) and through 'labor', or culturally guided human action. The sociometabolic model is described in the following section as an interrelation of stocks (human population, territory, livestock and artifacts) and flows (energy and materials). It has systematic similarities with national accounting and is thus useful for addressing many research questions, such as the resource productivity of a national economy or its energy intensity. To some extent, it is the description of an economy, at any time in history, using biophysical instead monetary parameters.

Keywords Evolutionary success · Communication system · Colonizing interventions · Hybrids · Sociometabolic model

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2.1 The Basic Socioecological Model Revisited

Sustainability science requires a non-reductionist macro-model of society-nature interactions. Such a model should describe these interactions in a way that complies with the categorial frameworks of natural as well as social systems. The theory's scope must be capable of providing an explanation for why entities such as 'culture' or 'society' have been so successful under the conditions of organic evolution that an evolving species like humankind has become the dominant power on the planet.[1] It should allow us to grasp the enormous differences among various modes of human subsistence, such as hunter-gatherer, agrarian, or industrial societies, and to explain the transitions between them. We believe that a theory of society-nature relations relevant for a sustainability transition must allow for, if not promote, recourse to long-term, historical and archaeological perspectives and must be useful across a range of spatial scales. The theory should be equally compatible with the Natural Sciences, particularly Biology and the Technical Sciences, as well as the Social Sciences and Economics.

In the following paragraphs, we explore whether the socioecological model we developed (see Chap. 1; in particular Fig. 1.3) lives up to such standards. We discuss its ability to provide an adequate epistemological basis as well as a research program by explaining in detail the individual components of the model.

The model's principal logic aligns with the Cartesian differentiation between *res extensa* (the natural sphere of causation) and *res cogitans* (the cultural sphere of causation). The next section will seek to explain the meaning of such a 'cultural sphere of causation', or cultural systems, within the context of theories of evolution. In contrast to the classical Cartesian dualism, however, our model introduces areas of reality belonging to both 'spheres'. It is exactly these areas that constitute decisive 'hybrid' parts of social systems.

In the sections thereafter, we will explain our core concepts: social metabolism and colonization. Both concepts focus on the 'hybrid' parts of social systems.

2.1.1 Why Talk About Culture? A Digression into Evolutionary Theory

To a substantial degree, we owe this model to a long-standing intellectual exchange with the environmental historian Rolf Peter Sieferle. One of his contributions consisted of an outline of the evolution of culture as a specific human evolutionary strategy (Sieferle 1997, 2011). Sieferle's point of departure is organic evolution, that is, the process by which changes in the genetic composition of

[1] Cf. the increasingly influential concept of 'the Anthropocene', which names an entire geological era after the dominant human species (Crutzen 2002).

populations of organisms occur in response to environmental changes. In the following paragraphs, we briefly reproduce his line of argument.

Each organism has a distinct identity. It lives in a temporal continuum such that its identity does not change during its individual history. An organism is also a morphological unit, a physical body with clear borders and the ability to defend these borders, to repel intruders and to heal injuries. In the functional center of an organism, there is an information complex, namely, its genome, which is fixed on a physical substrate (i.e., DNA or RNA) containing instructions that guide the synthesis of a larger physical complex, the organism's phenotype. The genetic information, however, does not solely lead to the development of the organism itself. It also leads to the synthesis of extrasomatic artifacts, such as spiders' nets or birds' nests—a feature Dawkins (1982) dubbed an 'extended phenotype'. From this perspective, modifications of and control over environmental conditions are not solely privileges of the human species. Along the same vein, there is learning, and thus information storage, in the nervous system of animals beyond the information encrypted in DNA. In many cases, however, individuals cannot communicate this information to other members of the species, and thus it is lost with the death of the individual. In many other cases in the zoological realm, individually acquired information is transmitted to other members of the same species without being fixed in the genome. Examples include the specific itineraries of migratory birds or the choice and use of tools by apes. In such cases, information does not flow only from parents to offspring but in any direction, avoiding the slow path of inheritance by variation and selection and permitting a much more rapid spread. Thus, culture is not restricted to the human species. However, its predominance as a strategy is specific to human populations. Sieferle asserts:

> Cultural tradition as such, that is non-genetic acquisition, storage, processing and transmission of information is not a specific feature of humans. A specific human feature, however, is to make this strategy dominant… Cultural evolution proper stabilizes the tradition of behavioral complexes by intergenerational transmission of information in human groups. This is the basic strategy of *Homo sapiens*, its evolutionary special path… When cultural evolution started, it continued organic evolution, and its emergence must have been awarded as a successful adaptation… Culture is not, however, merely an instrument of adaptation. Culture developed specific system properties that soon gave it characteristics that are not exclusively adaptive. (Sieferle 2011, p. 317)

Why was the emergence of culture awarded in evolution, and what renders it a successful strategy? Sieferle explores three possible explanations: culture might provide benefits for coping better technically with environmental conditions; culture might have been preferred in sexual selection; or culture may have benefitted intragroup cooperation. He opts for the third explanation: cultural evolution can be understood as a way to constitute stable cooperative groups of biologically unrelated persons; culturally defined groups can be more easily circumscribed by the use of symbols than genetically distinguished groups, with the chance of rapidly redefining boundaries; and cheaters and free riders can easily be identified and discriminated against. Thus, cultural evolution is primarily a social phenomenon and serves to help people address problems of complexity within groups, producing highly integrated and delineated 'pseudospecies'.

In organic evolution, when selection acts mainly in one direction—from the environment to the phenotype—a stable adaptation can be Sieferle argues that cultural evolution represents a positive feedback loop. Social expected. In contrast to this view, communication is recursive, and content is transmitted back and forth between members of a community so that patterns of plausibility rapidly emerge and move in any direction. Thus, a one-way adaptation to given circumstances is complemented or even replaced by open self-referential dynamics that allow for a high degree of freedom and velocity. 'In this sense, cultural evolution is a phenomenon *sui generis*, it is not an organism's (or a species' or a population's) method of survival. It has a high potential to depart from its original function, to generate peculiar autopoietic traits…' (Sieferle 2011, p. 311).

2.1.2 Society as a Hybrid System

This evolutionary reading of culture as an autopoietic system is one of the foundations of our socioecological model. It explains why we do not regard human societies as mere subsystems of the biosphere, and it complies with the sociological understanding of social systems as systems of recursive communication (Luhmann 1997/2012). Because the purpose of our theory is to understand society-nature interrelations, in contrast to Luhmann, we choose the term 'social system' for the structural coupling between a (cultural) communication system and interconnected 'hybrid' elements (see 'hybrid sphere' in Fig. 2.1) depending on the type of social system. The term 'social systems' can be applied to households, communities, cities, nation states, or organizations.[2] These social systems serve different functions. Each of them links a specific communication system with a human population, a set of artifacts and, eventually, animal livestock (see Fig. 3.1). We borrow the term 'hybrid' from Latour (1991), who uses it for material objects that are cultural artifacts and whose biophysical and cultural features are inseparably interwoven.

In what sense are humans, domestic animals and artifacts hybrids? The human population consists of organisms that must reproduce themselves biologically. Each individual possesses a consciousness that constitutes and reproduces itself through communication with others. Livestock consists of domesticated animals that provide services to humans, such as food, fiber, labor and the concentration of reactive nutrients. Of course, the reproduction of livestock is subject to biological processes, but it is also subject to long-term, culturally guided genetic selection by breeding (and possibly even by direct interventions in the genetic disposition of organisms by genetic engineering). Many behavioral aspects of livestock are culturally determined: where they live, what they eat, how they behave, if and with

[2]We use the term 'society' for social systems with the key function of sustaining a certain human population in a certain territory, such as local communities, cities and nation states.

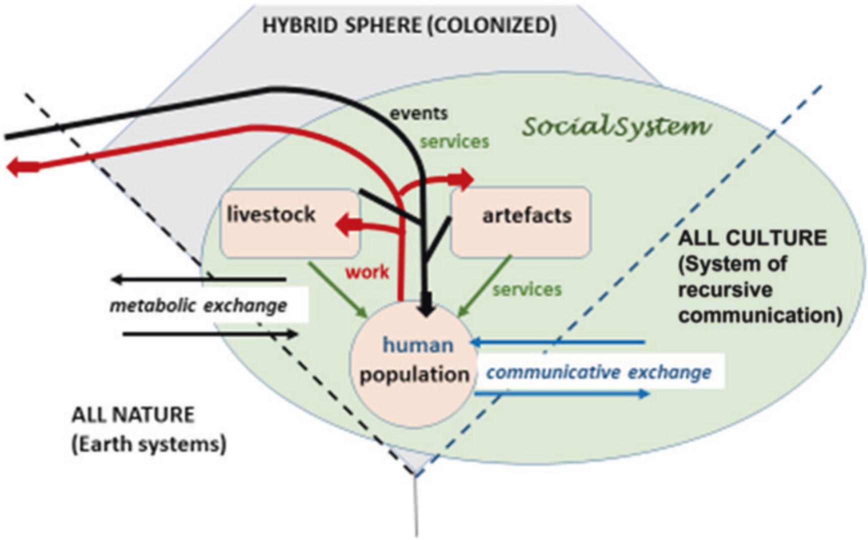

Fig. 2.1 Social systems as hybrid systems. (Detail from Fig. 1.3 in Chap. 1). *Legend*: The *green area* describes the social system; it extends beyond the hybrid sphere, crossing the dividing line into the cultural sphere. The human population, itself a hybrid phenomenon, is at the core of the social system. It connects to the cultural sphere by communication (*blue arrows*) and to the other hybrid and biophysical elements by experiencing events (*black arrows*), by performing work ('colonizing interventions', *red arrows*) and by receiving services (*green arrows*). All elements of the hybrid part of social systems engage in metabolic exchange with the natural environment

whom they mate and how long they live. Finally, all human artifacts, such as houses, roads, infrastructures, tools, machinery, vehicles, fixtures and fittings, are hybrids. A house is built according to a cultural program yet is subject to the laws of thermodynamics and to all sorts of natural impacts. The roof will develop leaks, the heating will break down, the façade will suffer weather damage—and if such natural processes take place without further intervention, the house will become uninhabitable and 'renaturalized'.[3] As long as the house is part of the social fabric, however, it is subject to a cultural program that determines what a proper house looks like, to whom it belongs and how it will be maintained.

In what sense do those elements 'belong' to a certain cultural (communication) system? On a generic level, the answer is simple and clear and follows from the basic assumptions about autopoietic (or autocatalytic) systems: it is the cultural

[3]Even an abandoned ruin is, of course, 'anthropogenic', but according to our understanding, it is no longer maintained by society and thus 'renaturalizes' and no longer belongs to the biophysical elements of society. It could also be 'reintegrated' once again, of course, and find use as a display piece.

system that defines and maintains its boundaries. Therefore, which human population, which artifacts and which livestock 'belong' to a certain social system is culturally determined (for example, by legal standards and property relations). This relation is represented within culture. Under concrete circumstances, of course, this boundary is complex and fuzzy, requiring specification by empirical conventions.

Within the cultural system, the core operation constituting the system is communication. What is the constituting operation of system formation among such diverse elements such as humans, houses and cows? We theorize the following. There does exist a constitutive operation, an operation we address as 'colonization' (see Sect. 2.3). Human beings are culturally 'colonized': they learn a certain language and a set of symbolic meanings and knowledge, they are socialized into certain norms and rules of behavior, they are guided by price relations in a certain currency and develop expectations about the behavior of others and they seek to mold their bodies in a way that suits a particular culture. This colonization permeates minds and bodies, but a substantial natural residue will remain: humans will always follow gravity even if socially embarrassing, will be plagued by diseases and will act out their desires in culturally inappropriate ways. It takes a continuous cultural effort to reproduce and modify human beings as suitable elements of the social system. The same type of operation is required to maintain and reproduce animal livestock as useful service providers; even more so, there is a tendency to 'renaturalize' and to require continuous colonizing interventions to feed, mate, give birth and die according to culturally prescribed modes. Nonliving elements such as artifacts that were produced according to cultural prescriptions renaturalize as well: they are subject to natural forces leading to an increase in entropy and demand continuous colonizing interventions to maintain their functionality for the social system.

We therefore think it is plausible to look upon the process of colonization as the core system-constituting operation between and among the elements of social systems, as specified in Fig. 2.1. Nevertheless, there is a substantial asymmetry between the human population and the other hybrid elements: only humans actively participate in the cultural discourse, and it is through their consciousness that cultural meaning is transformed into physically effective action.[4] The communication arrows between culture and the human population as the only one hybrid element illustrate this asymmetry (Fig. 2.1).

[4]On these grounds, Sieferle (2011) objects to including biophysical elements beyond the human population in the social system. We would maintain, however, that this distinction is somewhat fuzzy; it is not just animals that continue (at least for some time) to function the way they have been culturally conditioned (for example, laying many eggs or returning to a house). In the age of information and communication technology (ICT), many artifacts, as long as they are supplied with energy (which is also the precondition for humans), perform the tasks they have been designed for.

Why bother with such a complex and elaborate specification of social systems? As will become obvious in what follows and in many other chapters of this book, a sound understanding of system boundaries and of the necessary conditions of the self-reproduction of social systems is indispensable to conceptualize and quantify the metabolic exchange (see Fig. 2.1) between social systems and their natural environment as well as to understand conditions for sustainability.

The hybrid elements and the metabolic flows required to maintain them determine the social system's influence upon the 'rest of nature', with nature understood as the environment of the social system. This takes place, on the one hand, through the metabolic exchange of energy and materials (which, in part, occurs entirely unintentionally, such as breathing or evaporation) and, on the other hand, through 'labor'. Labor is understood here as intentional action with a given purpose (i.e., cultural meaning) that is physically effective. By means of work, interventions are made in natural conditions (both within and beyond the 'hybrid sphere'), which are thereby altered. However, purposeful changes, just like metabolism, also have unintended side effects, which the next level of intentional intervention will have to address. This involves societies in an ongoing control spiral (or risk spiral, see Müller-Herold and Sieferle 1998; Tainter 1988) and historical change.

These concepts—societal metabolism, colonizing interventions and their side effects—describe in large part what the Natural Sciences term 'human pressures upon the environment' (Smeets and Weterings 1999). The intended effects follow from the ways in which the social system functions: why and how does it pursue particular aims? The unintended effects, on the other hand, must be explained in terms of the functioning of the natural system. Society's pursuit of intended effects may ultimately be altered by this route.

In the natural 'environment', there are 'events' that affect the biophysical structures of society. These events can be ordinary processes such as rainfall, rust, or sun bleaching, many of which providing society with services, or more dramatic, rare events such as earthquakes, floods and epidemics. Events are either noticed or unnoticed by society and are (or are not) accorded certain meaningful interpretations. These meaningful interpretations take place in the consciousness of human beings, yet technical infrastructures can also provide cultural feedback (for example, measurement stations for air pollution). In any case, these meaningful interpretations must find a cultural representation in some form if they are to have effects on the cultural system. For example, the observation that bees are dying in huge numbers has to be communicated. Whether this communication culturally resonates as God's punishment (and so we must purge our sins) or as an insight that pesticide use in agriculture is poisoning bees is something over which nature has no influence—but communicating humans do wield such influence. Whichever interpretation prevails will provide cultural guidance to which responses to choose and will instruct human action.

Metaphorically, the relation between culture and the hybrid elements of social systems follows a hardware-software logic: the biophysical structures (including humans) are the hardware, and culture accounts for the software. If the hardware breaks down, the software loses its ability to work, but as long as it is functioning, the hardware behaves largely in accordance with the program. The program may also be altered (through communication). According to our approach, the actions (or behaviors) of human beings, cows, or power stations are seen not as culturally determined but as culturally guided by programs within particular spheres of action (which can also bring about failure, as the 2011 Fukushima nuclear disaster demonstrates). When these programs are put into practice, experiences are gained that may again find cultural representation, and through this, societal learning takes place.

2.2 Social Metabolism: Heuristic Definitions and Assumptions

The following section provides an overview of the key terminology in Social Ecology and an assessment of its consistency and usefulness. We discuss this in the following section in two parts: first, we focus on the terminology of societal metabolism; second, we look at the colonizing interventions of society in natural systems.

2.2.1 Sociometabolic Stocks and Flows and the Key Role of Population and Territory

The metabolism of social systems encompasses biophysical stocks, flows and—as we are gradually beginning to better understand, certainly in analogy to organic metabolism—the mechanisms regulating these flows. The starting point of sociometabolic analysis is the definition of the social system as a household, a business, a village, a nation state, or the global community. This definition will direct the research focus. It is important to note here that the social system defines its boundary; the boundary is not simply an arbitrary construct of the researcher. Delineating this boundary and deciding which elements are part of the system and which are not are decisive operations of the system itself. This presupposition is one of the lessons Social Ecology has taken from modern systems theory: a (complex) system constitutes itself through the marking and reproduction of its boundaries, and this fact must be recognized and respected from the research perspective. Social systems mark and reproduce their boundaries through the functions that they fulfill. Accordingly, they define their stocks and flows differently—along ownership boundaries, accepted entitlements, or governance responsibility, for example (see also Netting 1981, 1993).

In our past and current research, we predominantly focused on social systems whose function lies in the reproduction of a particular human population within

Table 2.1 Societal stocks and corresponding flows in empirical research

Stocks	Flows
Human population (structured according to age, gender, form of subsistence and other characteristics)	Demographic reproduction Migrations Lifespan/working time
All biophysical stocks (population, infrastructure, livestock, durable goods and tools)	Energetic input/output Material input/output
Territory (structured according to different characteristics)	Freshwater balance Net primary production (NPP) of plants Mineral resources

a particular territory. As explained above, we term this type of social system 'society' regardless of the scale at which this system operates. Both locally and nationally organized societies define 'who and what belongs' to them, or, more specifically, the biophysical stocks they wish to sustain and that they are operationally required to reproduce. This involves the biophysical stocks set out in Table 2.1, which require maintenance through corresponding flows.

Table 2.1 lists the societal stocks and their corresponding flows. A key component of a society is its human population; this is the actual point of reference regarding sociometabolic reproduction. Its size is significant in at least two respects: as the consumers of natural resources and as producers (labor power) who prepare natural resources for consumption and make colonizing interventions in natural systems. Their use of resources is determined by their way of life (as well as their demographic reproduction) and their level of consumption (in further chapters of this book, we discuss metabolic profiles and metabolic rates, see Chap. 3). Their role as producers determines the extent of intervention in natural systems through technologies and working time. A social system that cannot reproduce its population within certain varying ranges cannot maintain itself (see, for example, the fate of peripheral villages in industrial countries).

The size of the population engaged in exchange of this kind and its area density (i.e., the relationship between population and territory) was already viewed as highly relevant by one of Sociology's founding fathers, Durkheim, in his 1893 treatises (Durkheim 1893/2007) on the social division of labor. He regarded certain threshold values for population density as a prerequisite for the emergence of any kind of differentiated division of labor, and with this, specific forms of interdependence and 'solidarity'. The agricultural and development historian Ester Boserup (1965, 1981) has similarly analyzed the relationship between societal development and population density. In contrast to animal populations, for which a maximum sustainable population density—in ecology, termed 'carrying capacity'—exists, the interrelationship between territory and human population size is more complex and is determined by numerous factors, especially technology and, thus, technological change (Boserup 1981; Grübler 1998). Even in the case of hunter-gatherer or early agrarian societies, certain key resources (e.g., flints, salt) were exchanged over wide distances, and in modern societies, resource exchange via international trade is surging (Kastner et al. 2014a; Lambin and Meyfroidt 2011).

The territory as 'stock' is questionable. Is it a biophysical stock a society must reproduce? A territory is not only a natural space, a collection of given conditions within a topographical and natural area; it is also a political realm of power, within which particular interventions are legitimate. For this area, a society defines specific access and usage rights. Resources from the territory may flow into social metabolism without third parties thereby accruing rights to compensation. The human population present within this space is subject to society's operating rules. The functional boundary of the territory is maintained through operations of the social system, such as legal, military or economic activities, and the legitimacy of these operations is negotiated and needs to be recognized by other social systems, for example, neighbors or superordinate social systems. The spatial boundary is defined topographically. It is not a system boundary constituted through natural intersections, even if it may coincide with certain natural system boundaries, such as mountain ranges, watersheds, or water bodies. It soon becomes apparent that the area delineated by the topographical and the functional boundary need not be identical. In functional terms, for instance, the realm of power sometimes includes citizens who are located outside the territorial borders, whereas, conversely, some areas within the territory may have 'extraterritorial' status (e.g., the embassies of other countries). Water bodies often enjoy special status. The legal 'customs barrier' may, for example, be in the hinterland rather than at the coast, the topographical boundary.

Must societies 'reproduce' their territory? On the one hand, history is full of territorial conflicts; a social system that has its territory removed (or even only the resources offered by this territory, for example, through the diversion of a river) is doomed to fail. What role does the territory play in the metabolic reproduction of the social system's population? Of key significance is the fact that territory offers the population a legitimate physical 'common living space', that is, it serves as a 'repository for humans and their infrastructures' (Weichhart 1999). This 'repository function' provides the opportunity to participate in the consumption of the so-called 'free goods', the ecosystem services (Daily 1997a) within the territory (for example, clean air and water). In most cases, however, it means more than this. The state (or other political entities) is in some sense answerable to the 'common good' and thus to ensuring (at least minimal) conditions supporting the reproduction of its human subjects. In any case, at least within its territory, it must ensure that their metabolic reproduction is possible. The territory is therefore meaningful in containing natural resources which economic processes can appropriate. It also provides an outlet for the depositing of waste products from these processes, and it is a source of various non-provisioning ecosystem services.[5]

[5]However, under typical conditions, societies are not required to meet their own resource needs entirely from within their own territory but may regularly make additional use of the resource bases of other social systems (and, indirectly, of their territories) through exchange, trade or tribute obligations.

The relationship of a territory and its human population is not homogenous across space. Trade of resources allows for the emergence of differentiation among social systems. The earliest and most ubiquitous of these differentiations is that between urban centers and their 'hinterland'. A center-periphery structure regularly seems to appear when a territory acquires a certain population density (cf. Boserup 1981). However, we have been able to demonstrate elsewhere (Fischer-Kowalski et al. 2013, 2014a) that the size of urban centers and the share of their population relative to the population scattered across the territory and that provides their food is strictly limited under preindustrial conditions to a few percentage points.[6]

In particular, for agrarian societies, the energetic costs of transport and the human and animal labor power required to perform work are in direct competition with the products that require transportation as both depend on the same energetic basis, namely, the solar energy existing in the form of plant biomass. By this process, transport is translated into the energy required. In turn, this energy is translated into the area available for harvesting and into the labor power required to perform harvesting. This area is then translated into transportation distances, which must be overcome (Fischer-Kowalski et al. 2013; McNeill 2001; Sieferle et al. 2006). Model-based observations make it clear that the conditions of premodern agrarian societies place strict limitations on material flows between territories and that bulk raw materials (basic foodstuffs, sources of energy and construction materials) are used relatively locally.[7] There is an exception where territories are connected by advantageous waterways.

The availability of fossil fuel-based transport technology has lifted these constraints, resulting in a complex worldwide pattern of resource and commodity exchange across territories. Empirical research has shown that many mineral and fossil resources flow from low- to high-income industrialized countries and are directly related to or embedded in commodity flows (UNEP-IRP 2011). In contrast, international trade networks for biomass-based products are still dominated by directions of flow from sparsely to densely populated areas, almost independently of the economic performance of the individual nations (Erb et al. 2009b; Haberl et al. 2012; Kastner et al. 2014a, b).

Ester Boserup offers a different perspective on the interrelation between population and territory that is linked to the considerations detailed above

[6]However, researchers from the World Systems Theory have shown that under conditions of economic and social dominance, members of dominant societies can also draw on the resource bases of other territories under favorable military and transport conditions (Chew 2001; Ciccantell and Bunker 1998; Goldfrank et al. 1999).

[7]Under these general conclusions, of course, counter examples come to mind, such as the relatively wide geographic reach of marble for the opulent buildings of Antiquity or the reputation of Egypt and Spain as the 'bread basket' of ancient Rome. However, these examples only provide evidence for exceptional cases; one should be aware that these spectacular material flows constituted only a small share of the total metabolism of these societies.

(Fischer-Kowalski et al. 2014a). For her, a higher population density means, on the one hand, having access to a greater quantity of manpower and thus the opportunity to construct and maintain infrastructures (e.g., agricultural, transport) and to educate an intellectual elite capable of further developing these infrastructures. On the other hand, a higher population density means, as a matter of principle, lower resource density for the area (i.e., resource scarcity). Therefore, the advantages of higher density only emerge when technological or economic and military means outweigh resource scarcity. Nonetheless, the close connection between territory and the size of the population that can be sustained from its resources applies particularly to agrarian societies as their energetic basis consists almost entirely of solar energy stored in territorially dependent biomass. The same close link is not applicable to fossil fuel-based industrial societies, in which energetic supply does not depend on the size of the territory and in which machines can replace human labor. This replacement alters the relationship between requisite working power and demographic reproduction. Whereas under the conditions of the agrarian society, a vicious cycle among nutrition requirements, working power requirements and fertility rates prevails (which Boserup overlooks, cf. Fischer-Kowalski et al. 2014a), the conditions of industrial societies lead to a drastic reduction in fertility rates.

In contemporary industrial societies, the interlinkage between the sociometabolic requirements of the population and the territory has weakened and given way to globalized supplies. At the same time, the failure of the cultural systems of these societies to maintain a sufficiently integrated communicative base among their (increasingly culturally diverse) population segments within their territory is a major threat to system stability.

2.2.2 On the Relevance of Animal Livestock for Social Metabolism

Domesticated animals play a key role in the interaction between society and its natural environment. Livestock, comprising monogastric species such as pigs and poultry as well as ruminant species such as cattle, sheep and goats, can be regarded as 'live artifacts' providing essential services to humans. They deliver protein-rich food (meat, eggs and milk), fibers such as wool and hides, and building and handicraft materials such as bones and horn. The provision of technical power (draft power) that substitutes for human labor and reactive nutrients—contained in manure—that help prevent soil degradation in agriculture play a decisive role in a society's capacity for colonizing interventions in terrestrial ecosystems.

Preindustrial societies, in particular, vary markedly by the quantities of livestock they own. On the one hand, there is a difference between pastoral and cropland farming societies. Pastoral societies possess a large animal stock to make use of territories that are difficult to use in other ways because of unfavorable climatic conditions or topographic constraints. Cropland farming societies may possess varied stocks of animals depending on the demand for working and draft animals, the amount of marginal land that cannot easily be used for other purposes except grazing (e.g., high alpine pasture and forests) and the extent to which livestock provides fertilizer for cropland (FAO 2011; Krausmann et al. 2003).

Animal livestock is one of the key consumers determining a society's sociometabolic flows. According to thermodynamic laws, the provision of livestock products or services requires a substantially higher input-output ratio in quantitative terms. Large energetic losses are associated with the endosomatic metabolism of animals: as a rule of thumb, only one-fifth to one-tenth of their feed input is converted to growth (meat production), milk, or draft power, and the rest is lost to the maintenance of body functions. Furthermore, animals have to be kept alive in periods when their services are not required, such as during winter, when no mechanical energy is required on cropland fields.

Despite these inefficiencies, livestock plays a central role for many human populations. This becomes evident when abandoning the narrow perspective of efficiency in terms of biophysical input-output evaluation. From a broader perspective, many livestock systems appear particularly efficient. The services the animals provide, albeit associated with large feed requirements, come at little social cost. Livestock is, in principle, able to maintain itself and requires—depending on species and breed, of course—only a comparatively small labor input compared to cropping. Tasks such as herding and defense against predators are, to some extent, performed by livestock themselves quite naturally and efficiently (e.g., a cattle herd with bulls or a sheep herd with dogs) and thus require little input from humans. Livestock can also use areas that are far from the centers where their products are consumed due to their unique ability to transport the goods they provide, such as meat or muscle power. Beyond all this, the ability to digest biomass that is not digestible by humans, such as fiber-rich grasses or branches, makes livestock serve as highly valuable 'grazing machines'. Thus, livestock can indeed be regarded as a powerful means of expanding a society's resource base (Erb et al. 2012; FAO 2011; Herrero et al. 2013). Ruminant livestock can graze in almost all ecosystems, including forest understory, natural grasslands, shrublands and even semi-deserts—in short, land useless for cropping (see Chap. 13). This reduces competition for fertile land (see Chap. 14), and it broadens the source of nutrients for cropping. The German term 'Mistvieh', now a swear-word literally translated as 'dung-animal', can serve as a vivid illustration of this function of livestock: in Alpine preindustrial agriculture, old and otherwise useless domestic animals were not slaughtered but kept to feed from forests to extract nitrogen and nutrients, and their dung was collected for fertilizing cropland (Glatzel 1999).

Monogastric species (such as pigs) can also increase the efficiency of socioeconomic biomass use as they can be fed on biomass of lower nutritional quality and on food waste. Sharing a similar resource base, however, monogastric livestock can come into competition with human nutrition. From a materialistic perspective, the emergence of food taboos serves as a cultural regulation to prevent detrimental effects of this competition (e.g., Harris 1977/1991).

Thus, livestock represents a highly efficient means of colonization as a system with high input-output efficiency. In many preindustrial societies, livestock also plays a key role in safeguarding against environmental fluctuations. Its ability to maintain itself renders livestock a valuable living capital stock that can be liquidized (i.e., slaughtered) during harsh times but requires little maintenance during favorable times. This is a key aspect of livestock for food security that doubtless found entry in the many cultural regulations concerning the coexistence of humans and their livestock (FAO 2011).

In industrial society, with its virtually unlimited potential for increasing yields by removing the restrictions on area regarding transport and provision of fertilizer (McNeill 2001; Sieferle et al. 2006), livestock loses its central role as a working power and supplier of fertilizer. Animals are increasingly transformed into a supplier of food only, particularly protein, and the linkage between area and livestock numbers is loosened (Krausmann et al. 2008; Naylor et al. 2005). However, the global number of livestock has been increasing steadily, nearly doubling since 1961 (in overall numbers; in body mass, the increase is probably even greater). Today, cattle are by far the largest animal group on earth in terms of body mass, at twice the mass of human bodies (FAOSTAT 2014) and many times the mass of wild animals. This fact alone, particularly in light of their central role in human sustenance, makes it surprising that data on livestock and grazing is so scarce (see Chap. 13).

2.2.3 Artifacts, Infrastructure and Material Flows 'from Cradle to Grave'

In terms of quantities of metabolic flows, both the numbers of livestock and the stocks of built infrastructure have an impact. The latter are important because their construction and maintenance require space, flows of materials and energy, and working time. The overall functioning of the social system depends on infrastructure; society cannot function without supply structures for housing, water, gas, electricity, waste disposal structures, transport, power stations, river engineering, disaster protection, harbors and workplaces. Wiedenhofer et al. (2015), for instance, estimate that one-third of all nonmetallic minerals used in Europe are directed at maintaining existing stocks of residential buildings as well as road and railway infrastructure, illustrating their high maintenance costs as well as their long-term path dependencies and legacy effects (see Chaps. 19, 23 and 24). Failures to maintain infrastructures can put social systems at risk (see the debate on the collapse of the Roman Empire among Sieferle 2008, Fischer-Kowalski 2009 and Weisz 2009).

Defining practicable, meaningful and sound indicators and metrics that allow the complex nature of sociometabolic reproduction to be depicted has been a major challenge. For material flows of national economies, a methodology has been developed with intensive international cooperation (particularly with the World Resources Institute, the Wuppertal Institute and the Environment Agency of Japan, see Matthews et al. 2000). This methodology has become a part of standardized official statistics in Japan, the European Union and, increasingly, other parts of the world (see Fischer-Kowalski et al. 2011), and there are now annual reports on social metabolism at the level of nation states.[8] In our contribution to these international efforts, we have extended the accounting scheme from material flows to energy flows in a manner that complies with the above model of societal stocks. The now highly standardized methodological inventory of 'material and energy flow analysis' (MEFA) provides a biophysical accounting framework. It is rooted in the society-nature interaction model as described above and quantifies all flows in a social system that contribute to the reproduction of this system's biophysical stocks in mass (e.g., fresh weight, dry matter) or energetic units (e.g., joules, kilowatt-hours) and per unit of time, usually per year (see Haberl et al. 2004). The resulting indicators deviate from standard technical energy accounting by including the primary energy required for the endosomatic metabolism of livestock and humans. This conceptual bond of stocks and flows at the level of social systems has helped define system boundaries unambiguously and create a logical and clear accounting framework that is applicable at various scales and for very different historical periods.

It is no coincidence that the sociometabolic model has systematic similarities with national accounting—a connection used to address many research questions, such as the resource productivity of a national economy or its energy intensity. To some extent, the sociometabolic model is a description of the economy using biophysical instead of monetary parameters. Thus, the sociometabolic model accounts for the fact that natural systems react only to material interventions, as argued above.

Another important insight yielded by this model is that all input flows in a social system ultimately exit the system as output flows—the so-called 'material balance principle', which is ultimately grounded in the physical laws of thermodynamics (cf. the argumentation of Ayres and Kneese 1969). This provides an explanation of why many environmental measures to combat environmental pollution have proved inadequate. A dissipative system cannot be blocked from behind; to reduce emissions and waste, one must reduce the input into the system.[9]

[8]We have made great efforts (see also several related examples in this volume) to develop and apply an analogous methodology at other scales as well, such as local communities (see, e.g., Fischer-Kowalski et al. 2011; Grünbühel et al. 2003; Singh et al. 2001).

[9]Of course, it is also true that where such volumes are involved, certain qualitative parameters, such as the toxicity of material flows, fall by the wayside. Other measures, such as those from life cycle analysis (LCA; see also Method Précis Life Cycle Assessment), may also be consulted.

Finally, accounting flows on the system level yields the insight that the input flows of social systems are very different if measured in physical or economic values. For example, biomass in the form of food and feed constitutes a large share of the overall metabolism (approximately one-third in industrial societies and nearly 100 % in preindustrial economies), whereas it amounts to only a few percent in economic accounting. Similarly, the consumption of fossil fuels is far more important in biophysical terms than their monetary value would suggest.

There is yet another important insight, one that empirically emerged through analyses that compared the material flows of different economies, but is grounded in fundamentally different features of the economic and the biophysical life cycle. In the economic life cycle—from resource extraction to production, processing, trade and end use—monetary values exhibit a trend opposite that of material volumes. In economic terms, the value of a (future) product increases with each step in its preparation and processing. All the raw and auxiliary materials that will be incorporated in a product are, in sum, much less valuable than the product. The value of the product reaches its maximum at the point of sale to the end user. In the course of its utilization, the product progressively loses value, and when finally deposited as waste, it actually acquires a negative value (i.e., its disposal has to be paid for). As far as material volumes are concerned, the opposite is true: during resource extraction, large volumes must be set in motion with a corresponding amount of energy, and at every further step of processing, waste products and emissions are created, and the mass of the product as such becomes smaller. At the point of sale to the end user, the mass is minimal and finally also turns into waste or emissions (because, as we know, matter cannot cease to exist).

This insight is highly relevant when comparing countries with respect to their 'resource productivity' (an indicator measured as unit of gross domestic product, GDP, gained per one unit of material input). According to such a calculation, the national economy of Chile, for example, whose mining industry contributes half of the entire supply of copper to the world markets, has a high domestic material consumption (DMC/inhabitant) and a very low resource productivity (GDP/DMC). In contrast, a nation such as England, which imports almost all of its industrial products and specializes in banking and insurance services, has a very low level of domestic material consumption despite a much higher standard of living than Chile measured as GDP/inhabitant, and a much higher resource productivity. To grasp and interpret these differences, it is necessary to transcend the observation unit of one society by analyzing the network of societies interacting via trade. This can be done with the help of so-called hybrid multi-regional input-output models (MRIOs), both in monetary and physical units (Hertwich and Peters 2009; Lenzen et al. 2012; Peters and Hertwich 2004). By including the 'upstream flows' of imported (and exported) commodities, the so-called 'raw material equivalents' (RMEs) of traded products can be calculated (see Fig. 2.2 above and Schaffartzik et al. 2014), thus balancing the bias of a country's position further up or down the value chain. With the help of MRIOs, a new indicator for countries

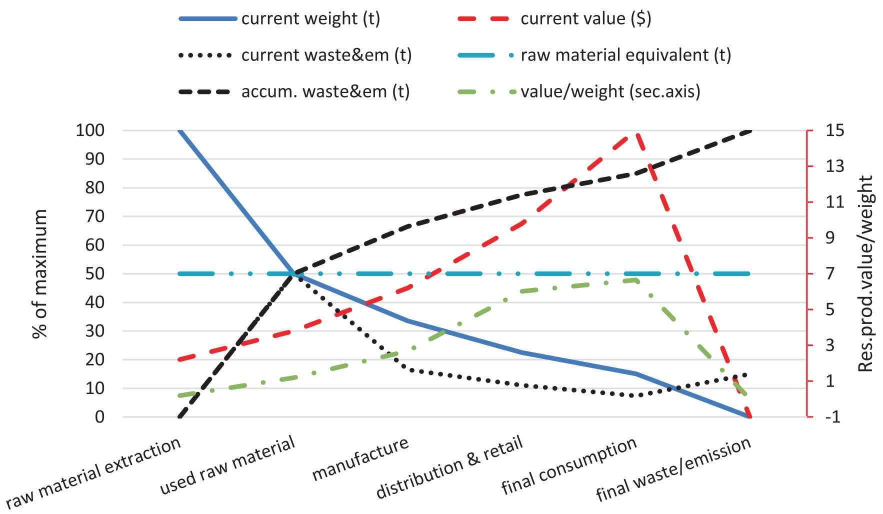

Fig. 2.2 Stylized model of the product life cycle, from extraction to production, consumption and deposition, in physical and economic terms. Model assumptions: From raw material extraction to used raw material, about 50 % of material is discarded (difference between 'total material requirement' and 'domestic extraction'); at each further stage, 33 % of the weight is lost to wastes/emissions. From one stage to the next, the value increases by a factor of 1.5 but drops to zero after consumption (stylized facts). The raw material equivalent (RME) corresponds to used raw material (domestic extraction, DE). See Haas et al. 2015 (For the meaning of the indicators and their abbreviations, see Fig. 1.1 in Chap. 1.). 'Value/weight' is typically accounted for as 'resource productivity'; the inverse is 'material intensity'

has been developed, the 'material footprint' (Tukker et al. 2014; Wiedmann et al. 2013). The material footprint (MF) portrays a country's share in the annual worldwide extraction of natural resources irrespective of whether the country extracts these resources directly from its domestic territory or draws on other territories by trade. Alternative complementary accounting systems that relate to land 'embodied' in the consumption of land-based products (i.e., biomass) are presented in Chap. 16 in this volume.

The rising monetary value of commodities along the stages of processing is, of course, due to the investment of labor and capital at each stage. Based on hybrid MRIO models, efforts have recently been made to quantify the amount and quality of labor input associated with traded commodities (Alsamawi et al. 2014; Simas et al. 2014a, b). This research allows the sociometabolic focus on single social systems, as depicted in Fig. 2.1, to be shifted toward the global network of human societies in biophysical and social terms. The monopoly of Economics in portraying the functioning of the world's societies is being challenged by the sociometabolic paradigm.

2.3 Colonizing Interventions in Natural Systems and Processes

Colonization[10] refers to 'the intended and sustained transformation of natural systems, by means of organized social interventions, for the purpose of improving their utility for society. A colonizing intervention must both be causally effective in changing some biophysical condition; it must make a difference in the world of matter. Likewise, it must be culturally conceived of, organized and monitored; it must make sense in the world of communication' (Fischer-Kowalski and Weisz 1999, p. 234).

Matter is stubborn. It is not sensitive to laws, money, good or bad intentions, aesthetics, or morals. To change matter, physical work is required, especially if it is supposed to be subjugated permanently (or for a long time) under a cultural or social purpose. Although humans are not the only species that 'changes the face of the Earth' (Marsh 1864), the degree to which humans do so is extraordinary. Although humans do change their natural environment by their metabolic processes, as explained in the previous section, colonization has a far greater impact. Colonization addresses natural systems across all hierarchical scales of organization (Fig. 2.3). It targets the level of atoms through exploiting energy flows caused by controlled (and uncontrolled) atomic decay, and it targets the level of macromolecules (particularly the genomes of many organisms) through domestication and genetic engineering. Furthermore, colonization alters the properties of molecules, cells and tissues, and it modifies organisms and their morphology and behavior. Some interventions are directed at entire ecosystems, such as the clearing of pristine forests for agricultural purposes.

2.3.1 System Theoretical Considerations

The concept of colonizing interventions builds on the theory of autocatalytic (Maturana and Varela 1987; Varela et al. 1974) systems. Many natural systems (certainly all live systems) are autocatalytic, that is, complex systems that cannot be 'controlled' or 'steered' from the outside. They can only be 'irritated'

[10]In any interdisciplinary field, it is advisable to use special terminology as sparingly as possible. It is important not to use a term stemming from a specific discipline in a markedly different way from its usual application, and it is important to avoid any choice of terminology that might foster the view that this particular discipline is in any way superior to others. In other words, we have to consider terminology not only as a tool serving the interests of research but also as touching on territorial and hegemonic issues between disciplines. With the term 'colonization', we refer to the Latin term *colonus,* which means farmer. In contrast, one may also associate the term with colony and colonialism, which refers to the subjugation and exploitation of a country by a dominant power. Both connections provide quite meaningful connotations.

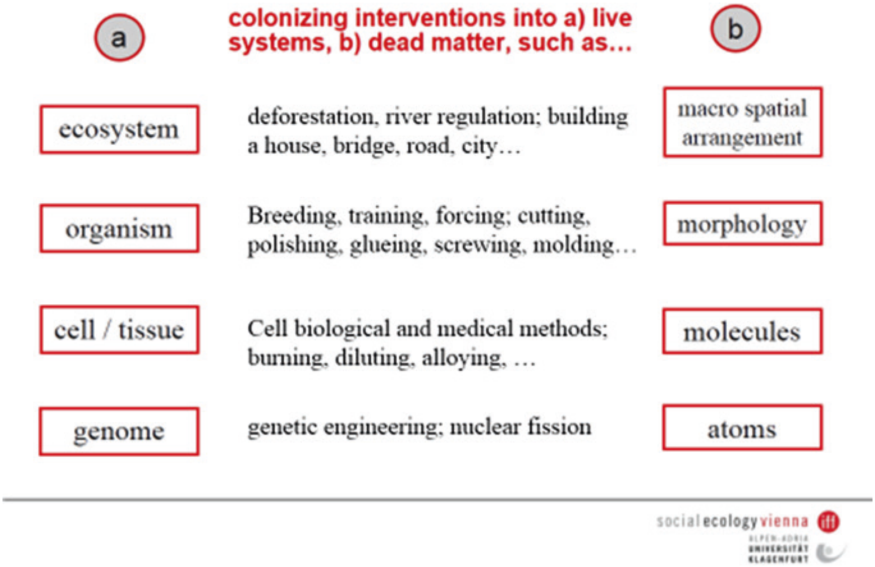

Fig. 2.3 Levels of potential societal colonizing interventions in natural systems

(to varying degrees, up to the point of destruction), always with some uncertainty in outcome and usually some unintended side effects. In organizational systems theory (e.g., Willke 1990), an outside effort at irritating a social system, with a particular goal or a certain intention in mind, is called an 'intervention'. We adopt this term to address a social system's effort to change the behavior of complex natural systems.[11] Usually, colonizing interventions seek to push a natural system out if its current state into a state beyond equilibrium, which is often a more fragile state. A pot is more fragile than a clump of clay; a river will continuously work on its dam to break it; a dog will forget how to obey; and a house will be washed away to the soil. Thus, there is a tendency for colonizing interventions to be self-denying, their objects falling back to their original equilibrium or some other state. There needs to be continuous monitoring and readjustment for the desired state (and the desired 'services' these states deliver) to be maintained. These interventions typically induce both intended and unintended changes in natural systems, sometimes at higher organizational levels. Intended changes in a grassland

[11]Let us consider, for example, constructing a chair from a piece of wood. The intention is clear: there exists a meaningful cultural program as to what features chairs should have. The intervention may still fail; the wood may not be homogenous and may break, or the glue may not stick. However, even if the end result is a nice chair, it is not a physical object under perfect social control. It still follows its natural destiny: the wood evaporates, worms may start eating their share or the surface may rot. I take continuous intervention to prohibit these natural fates—or else relinquish the chair altogether.

ecosystem may result in microclimatic alterations that then influence the entire landscape. This interplay between intervention and unintended consequences can lead to a control spiral: over time, interventions may have to be intensified or shifted altogether to achieve the original goal. This dynamic has been described by Müller-Herold and Sieferle (1998) as the 'risk spiral' and by Tainter (2011) as complexification and rising energy demand.

Do communication systems coupled with intensively colonized biophysical elements constitute complex systems in their own right, that is, 'hybrid systems' of the symbolic and biophysical realms? Would it make sense to claim that the structural coupling between a communication system and highly colonized natural systems is the essence of social systems and, indeed, that they constitute a second-order (hybrid) system across the fundamental differences of matter and culture? Would the operational closure of communication systems, or of ecosystems, necessarily be violated by such a theoretical construct? Is there something like an operational closure of the hybrid system? There are many problems to be resolved before an answer to these questions can be supplied.

Maturana and Varela (1975) used the term structural coupling to denote the relation between organisms and their environment. Maturana and Varela (1987) see the interactions between organisms and their environment as determined by the organism; the organism decides which components it extracts from the environment, and the organism's structures determine in which form they are being returned. Although numerous mutual causalities are conceivable, Maturana/Varela insist that changes in the environment may trigger changes in the organism, but they can never causally determine the metabolic processes of the organisms themselves. These arguments also very much reflect the processes we have addressed as social metabolism above (if we may, for the moment, equate the organism with the social system), and there we would fully agree with the Maturana/Varela point of view.

Our concept of colonization, however, draws an additional distinction between a colonized compartment and the rest of the natural environment. We would immediately agree that, biophysically speaking, the colonized compartment is no distinct entity—colonization is a matter of degree. However, the social system draws a distinction between colonized and uncolonized on the level of communication as well as operatively. It is defined by the communication system to which people, livestock and infrastructure 'belong'. These relations of belonging or property can be complex. For example, a factory may be on national territory and under its jurisdiction, but taxes may be due elsewhere, and the owner may not be a formal citizen of the country but a permanent resident. Moreover, these relations may not be well aligned among different subsystems. A relation of belonging or property does not imply complete control over something, but it does imply an interest in its reproduction and a certain liability, both of which are usually well represented within the communication system. This relation also matters biophysically. The metabolism of 'colonized' natural elements is typically taken care of socially. Thus, they become part of the social system's material stocks, and the flows required for their reproduction, by definition, become part of the social metabolism. Thus, in analogy to the Maturana/Varela perspective, the metabolic processes of social systems are determined by the functional requirements of those biophysical elements that are communicatively defined as ‘belonging’ to them and that are considered worth reproducing.

Boundaries, however, are fuzzy. They are fuzzy in the social definitions of ‘belonging’. For example, whether a certain road ‘belongs’ to a municipality and needs to be maintained by it or whether the responsibility lies with the respective state may be ambiguously defined. Boundaries are also fuzzy in terms of causal control. For example, how much of the road’s present state is controlled by colonizing interventions on the part of the social system and how much is controlled by natural processes of weathering and plant regrowth is a matter of degree. Relations may become more sophisticated, of course, as the literature on socio-technical systems illustrates[12] (see Appelbaum 1997).

For live elements, boundaries become even more complex. With livestock, there are usually clear property relations, and both the metabolism and the biological reproduction of the animals are largely under social control. In the historical background, there has been a long chain of colonizing interventions in animal reproduction that have led to changes on the genomic level (see Fig. 2.3), something that one day may be achieved much faster by a direct technical intervention in the genome. However, most metabolic requirements remain a matter of the nature of the organism (and in this sense, it remains operationally closed). If the social system uses livestock as working animals, it also needs to intervene in their behavioral characteristics (organismic level in Fig. 2.3) to train them for certain tasks and make them abstain from certain unwelcome habits. The same, of course, applies to pets. For plants, the main social property relation is the land they grow on. Nevertheless, among the plants growing on someone’s land, large distinctions may exist concerning their degree of colonization. For example, there may be a carefully dressed flower bed where the plants have been genetically modified, have had additional colors injected into their roots (intervention in tissue, see Fig. 2.3), are carefully cut (intervention in the organism) and are sprayed with pesticides (intervention in ecological conditions, population dynamics, predator-prey relationships). However, an unwanted side effect of colonization may be that weeds take advantage of favorable conditions by, for example, freeriding on the watering. Traditionally, the plant’s nutrient and water intake can be influenced, but its biological reproduction is not so easily influenced. Modern biotech firms are working hard on extending their control over plants’ fertility, but sometimes they cannot achieve more than an intervention in the communication system, such as making the use of next-generation seed illegal, though it is still functionally possible.

Even if the situation remains relatively stationary, that is, if a continuous flow of colonizing interventions secures a continuous level of ecosystem services, a strong interdependency is created between the social system in demand of certain

[12] In this literature, an effort is made to define the social organization, its processes and rules and the technical equipment it uses for communication and production as one complex system.

resources or services and the natural systems (or elements) concerned. A steady flow of monitoring and labor is required to keep natural systems in a specific colonized state and to secure the flow of resources and services. To be able to provide these benefits, communication processes and social organization have to be set up in specific ways and have to be readjusted if there is any change in the natural systems.

In the real world where interdependencies are dynamic, the social system is continuously under threat of losing its resources and services. The natural 'partner system' has to be maintained in a certain state, which in itself is subject to fluctuations and variations. Society thus has to reorganize itself permanently to secure its ability to provide the continuous flow of work, energy and materials required to maintain the natural system in its colonized state. This reflexive mechanism ranges from individuals having to organize to be able to regularly take their pills (i.e., a medical colonization of the human body), to dog owners who need to find the time to walk their dogs regularly, to villagers having to take care of the uphill forest to protect them from avalanches, to communities having to organize their communal budget and institutional regulations for protection against hazards, to employers depending on the functioning of the public transport system for their workers to be in place, and so forth. In effect, one may see this relation as a structural coupling between the cultural or communication system(s) and particular highly colonized natural systems intimately linked to them in mutual functional interdependence. In that sense, every social is a hybrid entity resulting from the structural coupling (achieved by colonizing interventions) between a communication system and a set of natural elements. One can presume a coevolutionary dynamic, as suggested in Fig. 2.4: the social investment in natural systems with the intention of transforming them in a desired way would achieve at least part of the intended outcome, would change the natural system and would lead to certain returns in terms of resources or services. The supply of these resources/services would in turn change the social system, adjusting it to this inflow. In parallel, the required investment of time, energy, materials and attentive observation would transform the social system (e.g., population dynamics, time and labor organization, technology development, education and energy supply).

Here again, the work by Boserup (1965, 1981) provides illustrious examples. In the long run, a preindustrial society achieves higher agricultural yields per area at the price of higher labor investments, which in turn allows for or even stimulates population growth and again increases the need for higher yields (see also Fischer-Kowalski et al. 2014b). A similar coevolutionary dynamic can be illustrated for the case of oil. As a country such as the United States (US) gradually runs out of this resource (as occurred in the 1970s) and because it has built most of its economy around it, it needs to shift to imports. In so doing, it transfers a large amount of money to countries that can supply this resource but do not have a modern structure. Thus, resources flow into (from the enlightened 'modern' view) archaic structures that feel culturally threatened and in turn pose major security risks to the US (and other 'modern' societies). To better cope with this situation, the US shifts toward the new colonization strategy of fracking in its own territory,

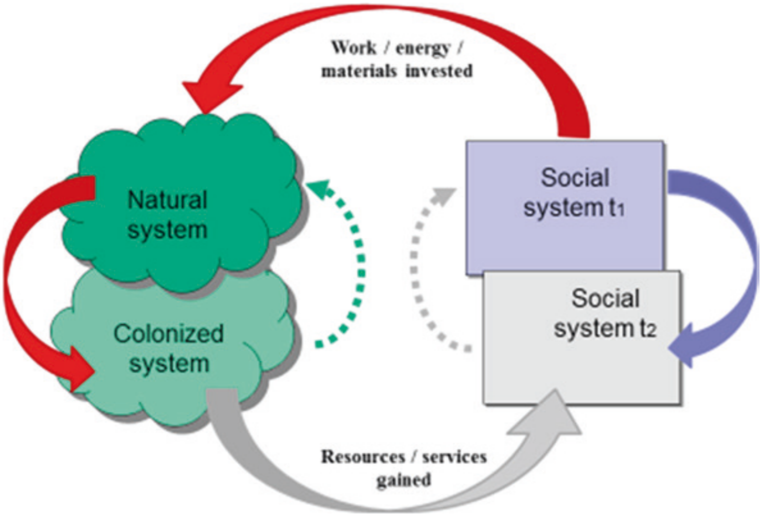

Fig. 2.4 From a control spiral induced by colonizing interventions to a structural coupling of social and natural systems

a well-stimulation technique in which rock is fractured by a hydraulically pressurized liquid. This technique requires a much higher labor and energy input and is associated with many detrimental effects on the land. The full coevolutionary cycle might end with both the need for higher security investments and higher investments in energy generation, and with it, more environmental damage.

On a more generic level, Tainter (1988, 2011) has described such processes of increasing mutual interdependency in his theory of societal collapse. He claims that societies build up complexity in their effort to resolve the problems that they encounter. An increase in complexity is always related to a need for a higher resource input, which results in a self-defeating process; each additional increase in complexity contributes less to problem-solving. However, although Tainter describes this process as purely social (with resources coming in as some passive element from the environment), we feel it could be better framed as a coevolutionary process: the changes in the environment due to societal problem-solving generate much of the problems that need to be solved.

2.3.2 How Can the Concept of Colonizing Interventions Be Made Operational?

The points of departure of our theoretical conception of metrics for colonizing interventions were simple. On the one hand, there was peace-researcher Johan Galtung's concept of 'structural violence' as an extension of direct violence. This concept refers to actions upon an external subject/object that diminish its chances of self-realization (Galtung 1969). In the face of the early 'deep ecology' debate and an empathic standpoint toward all forms of life on earth, this concept fits well as a critical element in the notion of colonization. Following this line of thinking, colonizing interventions should be all the more intense the more they tip a natural system away from its inbuilt dynamics or from its natural equilibrium. The implicit moral component of this idea only makes sense with live systems that can be imagined to suffer from such an intervention. The functional component bears some relationship with Latour's (2000) theory of actants. This theory does not assume natural elements to be passive objects of human action and technology; rather, they represent endogenous dynamics beyond human control. The colonization concept, however, stipulates a lesser degree of symmetry between social and nonsocial 'actors' than suggested by Latour: on the human (the social) side, there are intentions, success is monitored and reactions are modified accordingly; the natural system does not 'intend' and does not monitor and react to changes in the social system.

On the other hand, there was the idea to quantify the intensity of the intervention as proportional to the effort the social system puts into it. This effort could be expressed as the amount of human labor (measured, for example, in time units) on the one hand and the amount of technical energy invested on the other. In Land-System Science, such metrics are widespread, particularly in agronomic research. In combination with output metrics (e.g., agricultural yield), they have been used to describe the production function of land agriculture (and, less so, forestry), and, following the law of diminishing returns, they can be used to economically optimize land-based production (Erb et al. 2014). The biophysical indicator 'energy return on investment' (EROI; Hall and Klitgaard 2012; Hall et al. 2009) builds upon such metrics and has proven useful to describe the socioeconomic process underling land-use transitions (Krausmann et al. 2003).

However, the intensity of intervention is not necessarily a robust indicator of the effectiveness of colonization. A high amount of effort can be very ineffective at achieving a desired state of the natural system; vice versa, a small—and even declining—amount of input can be very effective in achieving a colonization goal. This discussion was punctuated by a publication by Schmid (*Magie in der Kolonie* 2006, or 'Magic as Colonizing Force') that experimentally suggested that magical rites be considered modes of colonization. Could we consider extensive rain-dance rituals performed with enormous effort to be colonizing interventions? This debate reinforced the idea that both the effort on the part of the social system and the effectiveness in changing natural conditions needed to be part of the concept. That effort mattered was well illustrated by a series of publications from our team that investigated the so-called Biosphere II experiment in Arizona (Haberl et al. 1998; Winiwarter 2000). This experiment at creating and running a quasi-artificial world in a materially closed glasshouse container was interpreted by the authors as an effort at 'total colonization'. The experiment failed; despite a tremendous effort in data management and an enormous continuous input of energy (28,000 gigajoules, GJ, per 'bionaut' per year—the European average is 200 GJ per inhabitant per year!), the bionauts lost weight and had to work much more than expected to manage the ecosystems and obtain a necessary minimum of food, oxygen and water.

A stringent empirical operationalization of the colonization concept on generic terms remains a challenge. The analytical framework 'human appropriation of net primary production' (HANPP), provides an example of such an operationalization for the broader field of 'colonization of terrestrial ecosystems' (see also Method Précis on Human Appropriation of Net Primary Production). Net primary production (NPP) denotes the annual biomass production of autotrophic organisms (mainly plants), that is, the balance between gross primary production and autotrophic respiration, and is a key process in the Earth system, providing the energetic basis of plant growth as well as for the trophic energy supply of all heterotrophic species, including humans. The HANPP concept had already been proposed in the late 1980s by Vitousek et al. (1986), motivated by questions about the scale of human activities within the context of global natural processes (Lieth 1973; Whittaker and Likens 1973, 1975). According to Vitousek et al., HANPP shows a huge range depending on the inclusiveness of definition, amounting to 3 % if only final biomass products are accounted for and up to 38 % if all NPP 'co-opted' as well as potential NPP losses are accounted for. The theoretical background of 'colonization theory' allowed the development of sound and meaningful definitions and the introduction of system boundaries that enhanced the analytical quality and the suitability of the HANPP indicator as an environmental pressure indicator (Erb et al. 2009a; Haberl et al. 2007, 2014). These further developments provided guiding principles for empirical research, much of which is documented in this volume (cf. Chaps. 14, 16, 17, 18 and 22 in this volume).

In this definition, HANPP indicates how much of the potentially available annual plant biomass production (NPP) is appropriated through human colonizing interventions, through deliberate changes of the land cover (for example, the conversion of pristine forest to grassland or arable land, or the sealing of soils by the construction of cities and roads) and/or through harvest. In other words, HANPP quantifies the difference between the NPP of the potential (i.e., hypothetically undisturbed) vegetation and the NPP that remains in the ecosystem after harvest. However, this indicator does not capture the social side of this process or the feedbacks on social structure. Two elements of these social features have also entered our empirical work: one is the labor burden in agriculture, which is dependent on colonizing interventions (see Chap. 26 in this volume), and the other is the issue of culturally molded diets. Diets may be considered an outcome of the coevolutionary process. A strongly meat-based diet results, as one possibility, from the existence of large but arid (or cold) lands that can support grazing animals but not farming, or it may result from abundant land in pioneer situations where there is still very low population density. However, the accustomed diet, reinforced economically, can lead to 'unadapted' colonization practices in regions that do not bear these features (e.g., the Netherlands), generating severe environmental side effects (that might trigger another coevolutionary dynamic). It can also lead to severe human health impacts by promoting overweight. For the world population, which is expected to become even larger, such diets will be unaffordable. Nevertheless, it seems difficult to leave such coevolutionary pathways.

Additional aspects of colonization entail an Environmental History perspective on society-nature interactions. In recent research, we analyze the coevolutionary pathways between a large river (the Danube) and the city of Vienna across five centuries (see Chap. 19 in this volume). This allows colonization to be localized spatially; the concept of socio-natural sites (*sozio-naturale Schauplätze*, SNSs) denotes a concrete place molded by a long sequence of colonizing interventions. A natural setting (such as a particular fertile region at a large river), as soon as it is occupied by people, is immediately modified by colonizing interventions. The particular interventions are part of the culturally predefined practices by which people at a certain time seek to meet their needs. They depend on their cultural repertoire, and they depend on the opportunity structure the environment offers. In all cases, they need to address food and shelter, securing the energetic and material metabolism of the group now and into the future. At these SNSs, material arrangements are created (by colonizing interventions) that are favorable for certain historical practices under the given opportunity structures. These socio-natural arrangements in turn facilitate certain practices and inhibit others: paths invite movement, whereas fences prohibit it. Natural arrangements have a similar selective effect: a large river makes crossing difficult, but it eases downward transportation; it threatens its surroundings with flooding, but it also fertilizes the land. If material arrangements are to favor certain practices, a continuous flow of labor and materials must be invested in their maintenance (colonization). The relationship between socio-natural arrangements and practices is coevolutionary. Arrangements (such as city walls) may become an obstacle to certain practices (in the case of population growth, for example), or they may provide an opportunity structure for unwanted practices (enemies may use the bridge across the river). When reconstructing the history of a river course and a city that lives at and from the river, these concepts relating to colonization have proved empirically useful.

Another approach, also with a historical note, seeks to quantify human labor time in relation to the colonizing practices employed. If it is correct to assume that colonizing interventions, within a sociometabolic regime, have a certain self-defeating tendency, then the requirement of human labor time should increase the longer the particular regime is in place. This time may come to a limit if human self-reproduction time (sleeping, resting, eating and hygiene) is squeezed too far to allow for a healthy life. Using labor time in this way to compare the colonization effort required between different social systems and framework conditions has proved to be a fruitful empirical approach (see Ringhofer et al. 2014 and Chap. 7 in this volume).

2.3.3 Which Intellectual Services Does the Colonization Concept Provide in Contrast to Other Conceptualizations?

The mainstream conceptualization of relating society to the material world is dependent on technology. Technology refers to both the specific tools (from bows and arrows to steam engines, washing machines and computers) and the social practices utilized to address certain problems, such as cooking food with fire and moving around by car. There is a long intellectual tradition of relating changing social practices and social structures to changes in technology, to the extent that many believe technology is the core driver of human history (Grübler 1998). There is much less systematic inquiry into the concomitant changes of the natural environment that happen as a consequence of certain technologies. Framing the society-nature interaction around technology creates a story of increasing human control over natural processes and of unlimited progress; nature largely plays a passive role.

The concept of colonization is more modest and much more symmetrical. It does not suggest that one side could control the other but suggests a chain of coevolutionary mutual impacts that may completely run outside of human control. It also takes a wider range of social responses to problems into account, such as changes in fertility, rising or shrinking inequality and even changing need patterns.

An increasingly popular discourse centers on ecosystem services.[13] Ecosystem services denote the sum of services ecosystems provide for society. These can be provisioning services (e.g., the provision of food, feed and fibers), regulating services (such as carbon sequestration and water and air purification), or cultural services (nonmaterial services, such as cultural, spiritual, or recreational functions). At the very heart of this concept, originally formulated in the late 1990s (Daily 1997b), is the acknowledgement that ecosystems provide goods and products beyond those that are marketed and have a price. Most of these other services remain unpriced and are thus not subject to the regulating forces (of any kind) of markets. Thus, the effects of human activities on these non-provisioning services remain unrecognized and are often detrimental (Daily 1995; Foley et al. 2005).

Whereas colonization draws attention to what social systems do to nature, ecosystem services draw attention to what social systems need and get from nature, including the warning not to destroy the source of these benefits. The discourse on ecosystem services is very closely related to the discourse on nature conservation—in a situation that is conceived as fairly desperate (considering galloping biodiversity and habitat loss), it is an effort to appeal to human self-interest by attaching economic value to those ecosystem services that may come under threat. In this approach, society is identified largely with its economy. The economy is

[13]The recently founded journal *Ecosystem Services*, in its first issue, 1/2012, gives an excellent overview of the various features of the ecosystem services approach.

seen as the main regulatory force, but as poorly organized to adequately address the maintenance of ecosystem services (Farley 2012).

One might consider ecosystem services to be quite a complementary concept to colonization. Ecosystem services (although, perhaps, in a wider sense) are what colonizing interventions attempt to secure and enhance. When we relate colonizing interventions to the economy, we talk about their cost, whereas the ecosystem services discourse talks about the benefits. Thus, a closer interlinkage between the two approaches might prove productive.

Chapter 4 in this volume elaborates how the colonization concept can help bridge these two conceptualizations within the context of land-use research. The colonization concept, empirically operationalized by the HANPP framework, allows technological aspects of land-use intensification to be addressed. It provides data on the output intensity of land management (where output intensity denotes the output per unit area of ecosystems, such as agricultural yields) that can be combined with data on input intensity (e.g., capital or labor inputs) to study the production functions of land-based production. Concomitantly, the HANPP framework systematically assesses changes in ecosystem states that are intimately associated with the input-output relation of land-based production, that is, the alteration of the availability of trophic energy in ecosystems. Many unintended consequences related to land use are closely linked to changes in NPP, such as human-induced degradation and changes in biodiversity or changes in biogeochemical cycles, such as altered carbon storage and sequestration. These interlinkages resulted in the conceptualization of land-use intensity as a multidimensional process (Erb 2012; Erb et al. 2013, 2014), thus bridging technological and conservationist perspectives of land use.

2.4 Conclusions

The socioecological theoretical approach we have attempted to describe in this chapter is ambitious, and it draws more on social systems theory than may be easily accessible to many readers. This approach has seen international successes empirically: the notion of social metabolism[14] guided the methodological develop-

[14]We do not claim priority for discussing social metabolism. In 1991, Baccini and Brunner published a book on *The Metabolism of the Anthroposphere* (Baccini and Brunner 1991), and the book by Ayres and Simonis on *Industrial Metabolism* was—with quite a delay after the preparatory conferences under the same name in Tokyo 1988 and Maastricht 1989—published in 1994 (Ayres and Simonis 1994). In Fischer-Kowalski and Haberl (1993), the concepts of metabolism and colonization first appeared jointly. Fischer-Kowalski, then, was the first to situate the concept of metabolism explicitly within the traditions of social theory. In the *International Handbook of Environmental Sociology*, edited by M. Redclift and G. R. Woodgate, she was as bold as to announce society's metabolism as a 'rising conceptual star' (Fischer-Kowalski 1997). Her later reviews of the intellectual history of society's metabolism were among the most cited articles in the *Journal of Industrial Ecology* (Fischer-Kowalski 1998; Fischer-Kowalski and Hüttler 1998).

ment of material flow accounting (MFA) that is now common statistics, and the particular empirical reading of colonization as HANPP has made its career in the literature. These successes are due to two great virtues: the concept allows social and natural systems to be addressed symmetrically, taking explicitly into account the complex and distinct system characteristics on both sides, and it is applicable across all of human history, without a modernist bias.

Among the Environmental Sciences, it has gained a reputation for interdisciplinarity and for relating to the Social Sciences. Among the Social Sciences, gaining a stand is more difficult. Describing the economy in biophysical terms (which is what MEFA does) is a core theme of Ecological Economics, but it has no place in mainstream Economics. Sociology and Political Science are not well integrated, either among themselves or with each other, and neither may feel comfortable with an analytic and systemic perspective that does not leave much room for deliberative action. Apart from sociological systems theory, there is currently little coherent and comprehensive social theory. Among historians, the combination of a systemic and general theoretic approach, with findings represented largely quantitatively, appears very uncommon. However, if society is to find a more sustainable pathway, the task of creating theory and methods that provide guidance needs to be pursued.

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