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ORIGINAL ARTICLE

The dialectics of capital: learning from Gran Chaco

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Abstract
The critical impact of humans on the biosphere has led scientists to coin the term Anthropocene. The global environmental changes associated with it are happening under the aegis of capitalism. A transition towards sustainability requires a critical scrutiny of capitalism. The social–ecological system (SES) approach conceptualises the relationship between the socio-economic subsystem and the biosphere. However, in its various operationalisations it either treats the former as a black box or it fails to capture dynamic aspects. We address these limits and develop a Dialectical Socio-Ecological System (D-SES) framework, which combines process ecology with historical materialism, to describe the emergence and persistence of capitalist dynamics. We draw on data collected through fieldwork and desk research and deploy our framework to study capital-intensive agriculture in the Chaco Salteño, an important agricultural frontier in South America, obtaining some general insights. We open up the socio-economic subsystem and break it down into a lower-level material/economic sphere and an upper-level cultural/institutional sphere. Capitalist dynamics emerge out of the peculiar relationships occurring both within and between these spheres. This configuration shows the typical signs of autocatalysis. It attracts resources and capital to expand itself (centripetality). It becomes more complex and organised over time, fine-tuning production modes, cultures, and institutions (directionality). It is subject to the laws of competition and profit maximisation, which emerge independently from the individual actors and processes making up the system (autonomy). Finally, it engenders frictions, reflecting class antagonism between the direct producers and the appropriators of wealth. These frictions can become leverage points for a system's transformation.

Keywords Social–ecological systems · Dialectics · Process ecology · Historical materialism · Chaco Salteño · Capital-intensive agriculture

Introduction

Human activities related to the extraction of resources interfere critically with a number of earth processes at the global level, including the climate, species extinction rates and the nitrogen cycle (Steffen et al. 2015; Díaz et al. 2019). A significant part of the biosphere has been converted into a global production ecosystem (Nyström et al. 2019) with humans appropriating about 25% of the world's net primary productivity (Krausmann et al. 2013). Anthropogenic factors, including technological development and economic growth, play a crucial role in the over-exploitation of the resource base (Cumming and von Cramon-Taubadel 2018; Dajka et al. 2020). Importantly, almost the entirety of food, feed and raw material production and distribution today happen within a capitalist system (Milanovic 2019), leading some authors to put forward the idea of "Capitalocene", as opposed to Anthropocene, to stress the role played by capital accumulation in particular, rather than some generic human nature (Altvater et al. 2016). Capitalism is here defined as a socio-economic system, intended as the historically developed articulation of modes of production, social reproduction, cultures and institutions. This system is centred around the process of capital accumulation, to which the satisfaction

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of human needs is ultimately subsumed. The tenets of this system are private property, wage labour, market exchanges and the competitive search for profits (Meszaros 2000). Capitalism is extremely productive, as witnessed by the accumulation of large amounts of wealth, globally estimated at 360 trillion US$ in 2019 (Shorrocks et al. 2019). The laws of competition dictate that this wealth must be continuously reinvested, leading to the continuous expansion of the global economy with important consequences for the biosphere (Ceddia 2020b). For example, there is increasing evidence that the investment decisions of a relatively small number of super-rich individuals and financial intermediaries are responsible for agricultural expansion and deforestation of tropical and boreal forests (Galaz et al. 2018; Ceddia 2020c).

The social–ecological system (SES) approach (Berkes et al. 2000, 2008) openly acknowledges the interrelations between social and ecological systems. Operationalising and implementing the SES approach has led to the development of several frameworks, here intended as a collection of elements, concepts, general relationships among those elements and values underpinning how a certain reality is viewed (Binder et al. 2013; Turner et al. 2020). Two of the most prominent ones are the ecological economic framework (Daly 1991, 2015; Daly and Farley 2011) and the SES framework (Ostrom 2007, 2009; McGinnis and Ostrom 2014). However, these frameworks suffer from important limitations: they either treat the socio-economic component of a SES as a black box or they are relatively static (Hinkel et al. 2014; Olsson et al. 2017). As human activities have become major drivers of planetary changes, understanding the history of the interactions between socio-economic systems and the biosphere is deemed crucial for sustainability transitions (Costanza et al. 2007). Capitalism is more than an economic system: it is strongly related to other social, cultural and institutional processes (Delanty 2019). Since capitalism permeates every aspect of our society, a critical scrutiny of its dynamics, their emergence and persistence and their relation to the biosphere is essential to the articulation of sustainability transition pathways (Feola 2020). The objective of this article is to address the limitations associated with some of the most important frameworks within the SES approach, to open up the socio-economic component of SES and capture in a systematic way the emergence and persistence of capitalist dynamics. To this end, we develop a new framework based on dialectics, by combining process ecology (Ulanowicz 1997, 2009, 2019) with historical materialism (Marx and Engels 1970). We label it Dialectical Socio-Ecological System framework (hereafter D-SES framework). Dialectics "comprehends things and their representations, ideas, in their essential connection, concatenation, motion" (Engels 1892, p. 32). For this reason, dialectics is particularly apt at capturing the dynamic aspects of a SES, while offering the opportunity to also identify the connections among its constituent processes. We deploy the D-SES framework to study the emergence of capital-intensive agriculture, on an unprecedented scale, in the Chaco Salteño in North-West Argentina. The region is one of the most important agricultural frontiers in the world, intended as areas of pervasive land use change mainly from natural habitat to agriculture (Lambin et al. 2001), and it is situated in the second largest forest biome in the South American subcontinent (Grau et al. 2015; Fehlenberg et al. 2017). By looking at the expansion of the agricultural frontier in the Chaco Salteño, we come to appreciate the value of our framework in capturing the specificity of capitalist dynamics and in shedding light on their emergence and persistence as historical processes. Finally, we identify possible areas of future research.

Theoretical building blocks

In this section, we introduce the building blocks of our approach, namely the concept of SES, process ecology (PE) and historical materialism (HM). We then combine them to generate our D-SES framework.

Social–ecological systems and complexity

SESs refer to systems that include a human socio-economic component, interacting with an environmental component (Berkes et al. 2000, 2008). The SES approach has led to the development of several operative frameworks. We here briefly report on two of the most notable ones. The ecological economic framework (Daly 1991, 2015; Daly and Farley 2011) stresses the embeddedness of the socio-economic component into the ecological component. The former is a subsystem of the latter, with which it exchanges both matter and energy (Fig. 1).

This approach has been quite important in framing the wider sustainability debate (Folke et al. 2016; Olsson et al. 2017). As already noted, in this framework, the socio-economic subsystem appears as a black box, making it difficult to understand what processes and relationships gave rise to it. The SES framework (Ostrom 2009; McGinnis and Ostrom 2014) obviates to this problem by decomposing the various elements of a SES into 8 first-level subsystems and 56 second-level variables. While providing a more accurate description of the socio-economic subsystem, the SES framework requires a large number of descriptors and it is static (Hinkel et al. 2014; Delgado-Serrano and Ramos 2015; Olsson et al. 2017).

To overcome these limitations, we will rely on the fact that SESs are complex systems (Preiser et al. 2018; Clark and Harley 2020). A system is complex when it contains a relatively large number of components that interact in a non-random way. The behaviour of such a system is not

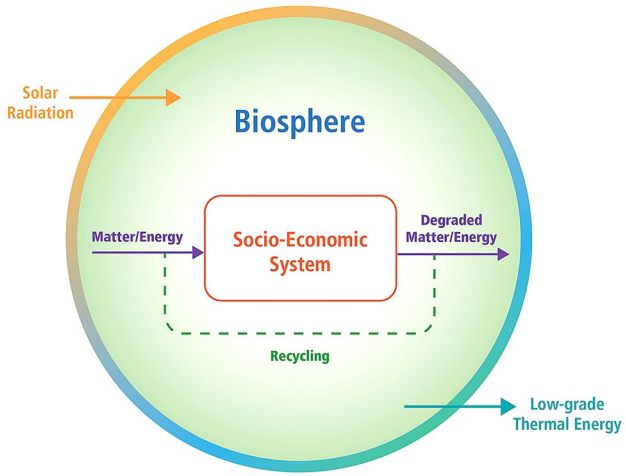

Fig. 1 The representation of a SES according to ecological economics. A social–ecological system represents the socio-economic system as embedded in the containing biosphere. The biosphere is a thermodynamically closed system, exchanging only energy (but not matter) with the outside environment. Solar radiation comes in the system and leaves the system as high-entropy thermal energy. The socio-economic subsystem is an open system, as it exchanges both matter and energy with the containing biosphere. Low-entropy matter/energy enters the system, which uses it to produce and reproduce; high-entropy matter/energy leaves the system. A part of the spent materials can be recycled, thus feeding back in the socio-economic subsystem. This figure is the author's adaptation of a pre-existing figure available under Creative Commons Licence (Source: https://commons.wikimedia.org/wiki/File:Diagram_of_natural_resource_flows-en.svg)

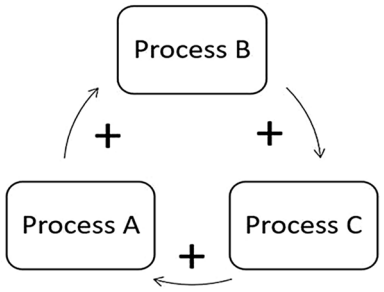

Fig. 2 Autocatalytic loop. The formation of an autocatalytic loop, as a concatenation of positive feedback (→+) among a set of processes (A, B and C). This figure is an adaptation of Fig. 4.1 in Ulanowicz (2009)

completely erratic but it is also not entirely determined, so that one speaks of organised complexity (Weaver 1948; Weinberg 2001; Bar-yam 2019). For example, the formation of patterns in agricultural landscapes, following the interaction among many land use decisions, is clearly not random (otherwise there would be no pattern) but cannot be determined a priori. The study of complex systems revolves around understanding how the relationships among parts lead to the emergence of organised behaviour at the system level (Bar-Yam 2004).

The process ecology perspective

Since SESs are complex systems, one is bound to ask how the organisation of the socio-economic subsystem emerges and persists and what its constitutive elements are. To address these questions, we rely on dialectics. Dialectics perceives phenomena in terms of interconnected processes (Ollman 2003). This approach is particularly apt for studying SESs, which, as complex systems, constitute themselves via relationships among processes (Preiser et al. 2018; Hertz et al. 2020; Mancilla García et al. 2020). Drawing on process ecology (Ulanowicz 1997, 2009, 2019) we begin by defining a process as "the interaction of contingent events on a set of constraints that results in a non-random but indeterminate outcome" (Ulanowicz 2009, p. 29). PE is strongly influenced by the dialectics of Alfred Whitehead, who noted how organised complexity results from the interactions between processes that dissipate and processes that organise (Whitehead 2010). When looking at systems through a process lens, some essential insights can be gained. First, the role of contingency, here defined as an event independent from the system of interest (Lewontin and Levins 2007), becomes clear. Any system is susceptible to disruption by exogenous events. The extinction of dinosaurs following a meteorite impact, or the death of a person accidentally hit by a car are sufficient examples. Second, order within a system is imparted via a set of constraints that limit the effects of disruptive contingencies. Systems do constrain the behaviour of their parts. We distinguish between two types of constraints that influence the dynamics of a system. The first one refers to autocatalytic loops. In this configuration, each process/node in the loop promotes/enhances the subsequent node (Fig. 2).

Autocatalytic loops present a number of interesting properties, which make them growth-enhancing (Ulanowicz 1997). Centripetality refers to the tendency of each process/node to draw an increasing amount of resources into the orbit of the loop, thus promoting its expansion (Xu et al. 2018). Directionality refers to the fact that with the passing of time autocatalytic loops tend to develop and become increasingly efficient (Ulanowicz 1997). During the development process, the autocatalytic loop exerts a selective pressure on its components (which denote lower levels in a hierarchical structure), constraining their behaviour and favouring those that are most beneficial to the whole loop (which represents the upper level in a hierarchical structure). Autonomy refers to the fact that such a selective pressure emerges at the upper level and is not obviously attributable to any individual lower-level component of the loop. Examples of autocatalytic configurations range from the diffusion of technologies when increasing returns to adoption exist, to

the evolution of an entire economic system (Schreyögg and Sydow 2011; Arthur 2014).

The second type of constraint is represented by centrifugal tendencies and negative feedback, which can manifest themselves at different scales (Xu et al. 2018). First, although during its development an autocatalytic loop tends to become increasingly organised, its persistence requires that a certain level of disorganisation/redundancy be maintained, to avoid brittleness (Ulanowicz et al. 2009; Goerner et al. 2009). In the face of adverse contingencies, it is out of this unorganised potential that the system will find the resources to either buffer the perturbation or develop into something else (Ulanowicz 1997). A converse example is given by monocultures, where the blind pursuit of maximum efficiency at the expense of diversity makes agroecosystems vulnerable to pests and diseases. Second, during the development phase, the autocatalytic configuration can come across a new node, which happens to be a better catalyser than one of the existing nodes. In this case, the new node would come in competition with one of the existing nodes and eventually replace it. Third, at a higher level, there can be competition among different autocatalytic loops for the resources available in the surrounding environment. This implies that there is always the risk that a certain loop can be supplanted by a more efficient one and/or that ultimately an autocatalytic configuration will encounter some limits to its expansion. These caveats are important since they remind us that each autocatalytic configuration always exists in balance with opposing tendencies. Without the presence of these centrifugal tendencies and negative feedback, systems would "explode".

To sum up, the behaviour of a complex system results from the interaction of contingencies, the order imparted by autocatalytic configurations and the limits imposed by negative feedback (Ulanowicz 2009, 2019). Such a behaviour is non-random (i.e. it is constrained) but still indeterminate (unlike a law). For this reason, the history of the system, here intended as irreversibility, does matter. Some of this history is recorded in the system's material configuration (Ulanowicz 2009). The emergence of a certain autocatalytic configuration may be initiated by contingent or accidental events. However, as the system develops, it becomes increasingly difficult for it to escape the constraints of the autocatalysis (Arthur 2014). In a certain sense, systems do have a memory (Nyström and Folke 2001).

Historical materialism

Historical materialism (HM) is a method, initially developed by Marx and Engels (1970), which posits that history proceeds from material processes rather than from ideas. HM is based on Hegel's dialectics (Hegel 2020), as re-elaborated by Marx. Dialectics sees processes as constitutive of things, rather than as derived from them (Harvey 1997; Lewontin and Levins 2007). Dialectics makes us think about reality in terms of processes that contain history and development and relations (Ollman 1993). For this reason, HM resonates very strongly with PE. The overlaps between HM and PE are many and worth being noted (for the direct quotes of the passages referred to below, please see the Electronic Supplementary Material). HM deals explicitly with the process of emergence of the whole capitalist system out of the interaction of its parts and in so doing tells us how the whole constrains and selects the parts, in a fashion that reminds us of autocatalytic configurations (Marx 1993, p. 278). With respect to the capitalist system, Marx and Engels very presciently write about its needs to constantly expand (Marx and Engels 2008, p. 6), reminding us of centripetality in autocatalytic configurations. Some of the key concepts developed in *Capital* include autonomy, objectification, and alienation (Ollman 1976). There are many passages in which Marx refers to capitalist dynamics as coercive, alienated forces confronting individual capitalists and society as autonomous powers (Marx 1990a, p. 381, Marx 1990b, p. 373). Here the connection with the emergent properties of complex systems, which arise autonomously from the individual nodes within autocatalytic configurations is evident. Additionally, being based on dialectics, HM grasps the transient nature of every historically developed form, which always contains contradictions (Marx 1990a, p. 103). The existence of contradictions reminds us of the importance PE assigns to centrifugal tendencies and negative feedback in the behaviour of complex systems. In fact, contradictions can be thought of as leverage points from which the whole system can be transformed (Levins and Lewontin 1980; Harvey 1997), in the same way in which centrifugal tendencies and disorganisation provide a reservoir for system development in the face of disruptive contingencies (Ulanowicz 1997). Within a socio-economic subsystem, these contradictions have their origin in the fact that the interrelations among different sets of processes involve agents with different positions with respect to the production and distribution of material wealth (Wood 1995a). In fact, as we will argue more in detail when presenting the results of our case study, these contradictions can be related to the concept of class antagonism (Wood 1995b). Lastly, HM is not blind to the fact that historical development depends on pre-existing conditions and that social systems do have a memory and as such they can be prone to lock-ins (Marx 2009, p. 1).

Opening-up the socio-economic subsystem through the D-SES framework

Having pointed to the similarities between HM and PE, our goal in this section is to bring them together under the D-SES framework and open up the socio-economic

subsystem to provide a succinct yet comprehensive description of its constituent processes. This task is facilitated by the fact that HM acknowledges the interrelations between the socio-economic system and the biosphere, in a way that is consistent with the SES approach. According to HM the "metabolic relationship with nature" is a transhistorical constant of human existence, while the particular shape such a relationship takes under capitalism is the result of historical processes (Marx and Engels 1970).

Through the lenses of PE, the emergence of the capitalist socio-economic subsystem can be seen in terms of interactions among processes, occurring within an environment. Such interactions involve the formation of autocatalytic configurations and the existence of centrifugal tendencies. This leads to the following questions: how do capitalist configurations emerge? What are the constituent processes? HM provides us with some important clues. We begin by looking at a crucial passage in which Marx succinctly illustrates the tenets of HM. While discussing the role of technological development, Marx notes how: "technology reveals the active relation of man to nature, the direct process of the production of the social relations of his life, and of the mental conceptions that flow from those relations" (Marx 1990a, p. 493). The first part of the passage refers to the role of technology in mediating the relationship between man and nature. However, it is the rest of the passage that gives us an indication of what the constituent elements of the socio-economic subsystem could be. Technology affects social practices, which include not only production per se, but also, social reproduction and the way of thinking. A further elaboration (Harvey 2017) allows the identification of six "moments" (or processes/nodes) constituting the socio-economic subsystem: technological processes, social relations, material production processes, daily life and social reproduction (i.e. material/economic processes), development of mental conceptions and institutional processes (i.e. cultural/institutional processes).

HM does not only give us a "list of ingredients", telling us which processes need to be considered to understand the emergence of the socio-economic subsystems and its functioning. HM also suggests that cultural/institutional processes emerge out of material/economic ones (Marx 1990a, p. 175). There is a long debate about this "base/superstructure" model, which we have no space to summarise (Wood 1995c). Here it suffices to say that, in our opinion, the quoted passage does not imply technological/economic determinism or a linear cause–effect relationship between the material/economic and the cultural/institutional sphere. Such an interpretation is supported by another passage in which Marx posits that any experience of the material/economic sphere is conditioned by the cultural/institutional sphere (Marx 2018, p. 12). The relationship between the material/economic sphere and the cultural/institutional sphere is therefore dialectical and consistent with the concept of emergence and constraint already mentioned when introducing PE.

To summarise, through the D-SES framework we can open up the socio-economic subsystem of a SES. We can explicitly spell out the six interacting processes/nodes originating from the socio-economic subsystem. The interactions are hierarchically structured along a set of material/economic processes (the "lower-level" loop), out of which a set of cultural/institutional processes emerge (the "upper-level" loop). These interactions, which involve both autocatalytic configurations (i.e. positive feedback) and centrifugalities (i.e. frictions and contradictions), describe a particular metabolic relationship with the surrounding environment (see Fig. 3). It is the interactions among the six moments and the associated contradiction that must be studied to understand the historical emergence of the socio-economic subsystem within a SES and capture the essential features of capitalist dynamics.

Materials and methods

We use the D-SES framework to study the emergence of capital-intensive agriculture in the Chaco Salteño. Data on this case study were collected through both fieldwork and desk research, within the research project on Indigenous Communities, Land Use and Tropical Deforestation (INCLUDE). The project team spent several months in the field over the

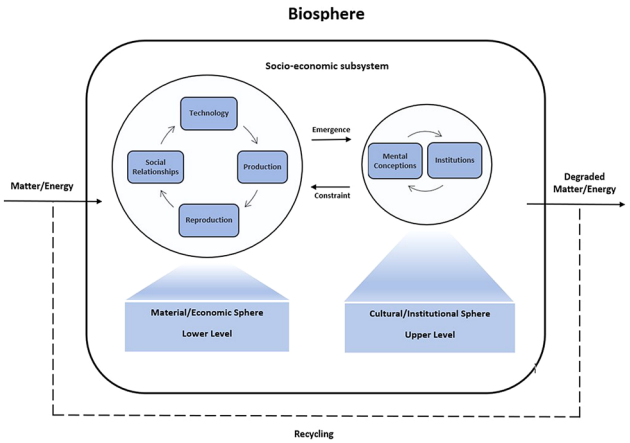

Fig. 3 Heuristic representation of the socio-economic subsystem of a SES. Drawing on HM, we describe the socio-economic subsystem of a SES as emerging from the dialectical interaction between the material/economic sphere (which itself comprises the interaction among technological processes, production, reproduction and social processes) and the cultural/institutional sphere (comprising the interactions between mental conceptions and institutional processes), where the latter emerges from the former. The upper level (i.e. the cultural/institutional sphere) constrains the lower level (i.e. the material/economic sphere). The whole configuration can be thought of as an autocatalytic loop

periods of April–August 2017, May–September 2018, and February–July 2019. During this time, the team collected a large amount of data via participation in workshops with local researchers, via semi-structured interviews with various stakeholders (including peasants, indigenous peoples, representatives of producers' organisations, NGOs, large-scale farmers, and public officials), via exchanges with local researchers and practitioners, and via field trips. Moreover, two of the authors (Montani and Mioni) are local researchers with long-term experience in the study region. Some of the data and information have been previously processed and analysed to answer specific research questions developed within the INCLUDE project (Ceddia and Zepharovich 2017; Tschopp et al. 2020, 2022; Zepharovich et al. 2020b, a, 2021; Ceddia 2020a, d; Inguaggiato et al. 2021a, b; Ceddia et al. 2022). A more detailed account of the data collected within the project is presented in the Electronic Supplementary Material.

As a result of this work of data collection and analysis, a wealth of knowledge on the Chaco Salteño has been accumulated. For this paper, we have complemented this information with further material obtained via purposeful literature searches. Both HM and PE converge on the importance of providing a historical narrative, here intended as an analytical account of the development of material relations (Wolf 2010). To this end, we draw on our framework (see Fig. 3) to interrogate the knowledge accumulated by the authors and generate a detailed exposition of the evolution of the socio-economic subsystem and its relationship with the surrounding environment in the study region (Crumley et al. 2018; Sinclair et al. 2018; Gergel and Thurstan 2021). We do this convinced that when dealing with SESs, the past may be our best laboratory (Crumley et al. 2017).

The anthropisation of the Chaco Salteño under capitalist agriculture: a history of its material configuration

The Chaco Salteño is one of the most important agricultural frontiers worldwide (see Electronic Supplementary Material for further information on this case study). The purpose of presenting this case study is twofold. First, we want to show how our framework can be used to open up the socio-economic subsystem and spell out the relationship between its various constitutive moments. To this end, we reconstruct the history of its material configuration and make sense of the emergence of capital-intensive agriculture in the Chaco Salteño. The approach developed here thus provides a lens through which certain phenomena can be interpreted in a systemic way and it directs the authors' focus on certain aspects instead of others. The narrative will try on one hand to emphasise the various positive feedbacks among the moments/processes that accompany the emergence of the whole system. On the other hand, it will point also to its internal contradictions (centrifugalities in the language of PE), the resistances which result from the antagonism between direct producers and appropriators and the resulting competition for resources between capital-intensive agriculture and other modes of production (Fig. 4).

Second, in telling the story of the Chaco Salteño, we would also like to extract some general insights about the specificity of capitalist dynamics and provide an outlook on future research.

Contingency and the inception of capital-intensive agriculture in the Chaco Salteño

PE explicitly acknowledges the role of contingencies in the behaviour of complex systems since any system is

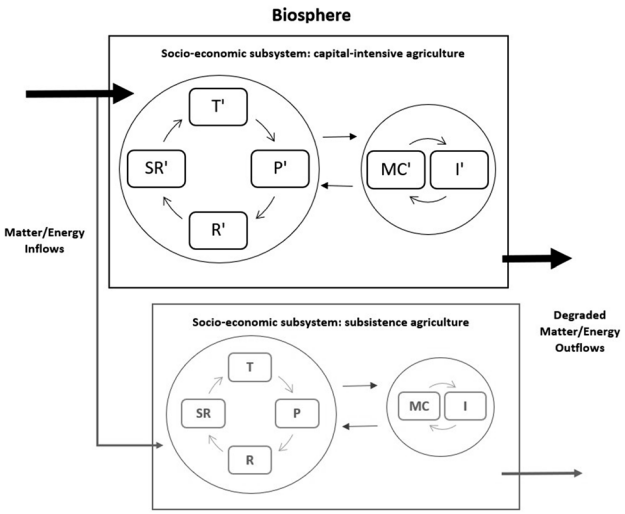

Fig. 4 The regime shift from subsistence to capital-intensive agriculture. The figure portrays the shift from the old subsistence agricultural regime to the new capital-intensive agricultural regime. The old regime was characterised by the old material/economic sphere and by the old cultural/institutional sphere. The former included the old technology T (e.g. horse), the old mode of production P (e.g. extensive livestock and hunting–gathering), the old social reproduction R (rural) and the old social relationships SR (patronal and/or non-market exchanges). The latter included the old mental conceptions MC (e.g. subsistence) and the old institutions I (e.g. common lands). The new regime is characterised by the new material/economic sphere and the new cultural/institutional sphere. The former includes the new technology T′ (e.g. GM soy), the new mode of production P′ (e.g. no-till), the new mode of social reproduction R′ (e.g. migration to urban centres) and the new social relationships SR′ (e.g. wage labour). The latter includes the new mental conceptions MC′ (e.g. profit maximisation) and the new institutions I′ (e.g. private property). The new regime absorbs a larger flow of matter/energy (thick incoming arrow) than the old one (thin incoming arrow). There is competition for resources (centrifugalities) between the two systems. The new regime ejects a larger amount of degraded matter/energy in the environment (thick outgoing arrow) than the old one (thin outgoing arrow)

vulnerable to disruption by external events. In the Chaco Salteño, the crucial event which led to the displacement of the old socio-economic configuration is the introduction of genetically modified herbicide-tolerant soy (GM soy hereafter). From the limited perspective of the Chaco Salteño, the arrival of GM soy can be treated as an exogenous shock, in line with our definition of contingency. Although forms of capital-intensive agriculture reached Salta during the 1970s (e.g. beans cultivation), the region remained largely marginal until the second half of the 1990s (Cáceres 2015). In 1996, Argentina authorised the commercial growing of GM soy. The crop expanded first in the Pampean region but quickly reached also the extra-Pampean regions, including the Chaco Salteño (Mioni et al. 2015). These developments mark the spread of capital-intensive agricultural production on an unprecedented scale and the concomitant expulsion and marginalisation of both peasants and indigenous peoples (Mioni et al. 2015). The arrival of GM soy in the Chaco Salteño represents the sort of contingency that brought down the constraints imposed by the existing cultural/institutional sphere (i.e. the upper-level loop) by changing radically the material/economic sphere (i.e. the lower-level loop). We examine this process more in detail in the following subsections.

Autocatalysis and the emergence of capital-intensive agriculture in the Chaco Salteño

Besides the role of contingent events, PE points to the order-imparting effect of autocatalytic loops. We, therefore, study the concatenation of processes since the introduction of GM soy leading to the emergence of a new socio-economic subsystem based on capital-intensive agriculture. Drawing on our framework, we will look at the interactions among the various moments that characterise the formation of the new socio-economic subsystem configuration, at the expense of the old subsistence agriculture (Fig. 4). We do so by looking sequentially at the lower-level loop (i.e. the material/economic sphere) first, and subsequently at the upper-level loop (i.e. the cultural/institutional sphere).

The lower-level loop: technology, modes of production, social relationships, and reproduction

The material/economic sphere refers to the interrelations among technology, production, social relationships, and social reproduction processes. These processes capture most of what should be of interest in analysing the material/economic aspects, while still utilising a relatively small number of descriptors. In the Chaco Salteño, the use of GM soy brought up several important changes in the production processes. First, GM soy relies on the use of standardised inputs and methods (GM seeds, pesticides, etc.), provided by agrochemical corporations and their extension services. Second, its introduction has been accompanied by organisational innovation, including the leasing of land and machinery to specialised subcontractors (Colina et al. 2012; Cáceres 2015) and the introduction of value-adding activities, such as the rearing of livestock in feedlot systems (Gasparri and de Waroux 2015; Cáceres and Gras 2020). This strategy, which aimed to achieve detachment from fixed capital, allowed the great flexibility necessary to respond to volatile market conditions (Gras and Hernandez 2016). Third, the production of GM soy as an international commodity relies on large-scale exporters and traders to reach the destination markets, and on the more prominent role of financial institutions to provide the necessary credit. The new agricultural production method is geared towards the generation of both profits for the private investors and foreign currency for the national economy. GM soy made the land of the Gran Chaco available to both domestic and international capital in search of investment opportunities capable of generating high rates of return (Lapegna 2016). Land provided a spatiotemporal fix (Harvey 1999), the physical space where the existing capital (including financial resources and machineries) could be deployed to generate an income flow and pursue further accumulation (Fairbairn 2020).

The expansion of capital-intensive agriculture has important consequences on the patterns of social relationships, which become increasingly centred around, if not incorporated into, market transactions (Polanyi 2001; Wood 2002). This point cannot be stressed enough. Under this new regime, the market is not a mere opportunity but becomes an imperative, as it is essential not only for the exchange of the outputs but also for accessing the factors of production (land and labour) and therefore for the social reproduction of the relevant actors (Wood 2002). Efficiency and profit maximisation become a necessity while impairing the social and cultural reproduction of peasants and indigenous peoples (Barraclough and Ghimire 1995). This process represents another positive feedback that further reinforces the spread of the capital-intensive mode of production. As a result, over the period 2002–2010, the area planted with soy in the province of Salta increased dramatically from about 100,000 ha to almost 600,000 ha, mainly replacing forests and shrub lands (Colina et al. 2012; Mioni et al. 2015). The penetration of capitalist relations into the reproductive sphere of peasants and indigenous communities has been a central theme of rural studies in recent decades (Bernstein 2017). For example, in the Chaco Salteño, the economy of peasants and indigenous peoples formerly relied on the work of family members or on the performance of small casual jobs (known as "changas"), usually within a patron–client relationship (Blaser 2010; Wolf 2013). This type of social relationship, which is essentially personal and non-contractual, gets substituted by wage labour under capital-intensive

agriculture (Garay et al. 2017). This implies a significant change in the relationship between the producers and those who appropriate the surplus. In pre-capitalist contexts surplus appropriation occurs mainly through force or political power (or both), which is integral to the overall production process. In capitalist relationships, appropriation is mediated by a purely economic transaction, the sale of labour power on the market (Wood 1995d). Between 2002 and 2018, the share of family workers in agriculture in Salta (denoting primarily a familist and non-contractual relationship) declined from about 37% to less than 13%. Over the same period, the contracting of specialised companies to carry out agricultural operations (e.g. clearings, soil preparation, sowing, application of pesticides, harvesting etc.) increased from about 20% (about 895,000 ha) to more than 38% (over 1.7 million ha) of the area occupied by agricultural enterprises with definite limits (Instituto Nacional de Estadistica y Censos 2007, 2021). These specialised contractors, in turn, rely on the exploitation of agricultural workers, who are required to be extremely mobile and who are uprooted from their families and communities, and are forced to live in appalling conditions (Villulla 2015; Garzón 2020). Finally, the limited job opportunities, alongside the expulsions, lead to further changes in social reproduction processes, for example, via the migration of peasants and indigenous peoples towards urban areas. Here they can either try to become wage labourers and consumers (another positive feedback to capitalist dynamics) or, more often, live under extreme poverty (and putting a downward pressure on wages). Between 1991 and 2001, in the province of Salta alone, migration from rural to urban areas led to an average increase in the urban population of almost 32% (Schmidt 2014). In the Chaco Salteño ecoregion, which only covers a part of the Salta province, the urbanisation of indigenous peoples increased significantly from 48 to 58.8% over 2001–2010 (Klarik 2019). The expulsion of indigenous peoples and peasants towards urban centres represent a new wave of proletarianisation common to other agricultural frontiers in Latin America (Kay 2004).

The expansion of capital-intensive agriculture in its material/economic dimension also absorbs an increasing amount of material resources (thick incoming arrow in Fig. 4) that are ultimately released in the environment (thick outgoing arrow in Fig. 4) causing significant social and environmental impacts that affect mainly indigenous peoples and peasants (Leguizamón 2016).

The upper-level loop: mental conceptions and institutions

Our approach explicitly posits the emergence of the cultural/institutional sphere out of the material/economic sphere, while at the same time constraining it. Technological processes (which represent one moment of the material/economic sphere) are not neutral and have the ability to produce new worlds both around and within us (Arthur 2009).

In the Chaco Salteño, we already noted how, under the new material/economic conditions, reliance on the market becomes a necessity. As a result, the expansion of capital-intensive agriculture has led to the diffusion of a dominant culture grounded in the concept of productivity and economic development based on market competition and profit maximisation (Gras and Cáceres 2020), further accelerating the expansion of the capital-intensive agricultural model and deforestation (Gasparri et al. 2013; Mioni et al. 2015; Fehlenberg et al. 2017). The "coercive laws of competition" face individual producers as something independent from them. They emerge autonomously out of the new material/economic configuration. As a result of these market pressures, in Salta, agricultural expansion and deforestation highly increased over 2002–2010 (Gasparri et al. 2013; Mioni et al. 2015; Fehlenberg et al. 2017). These events in turn brought about an important institutional change, which deserves further scrutiny. This change relates to the reactivation of the land market and the role of private property. In effect, following the surge in land values, legal ownership, intended as full individual alienable property rights mediated by the market, became the privileged mode of accessing land at the expense of all other forms (e.g. usufruct, possession, illegal occupation etc.). We note that the institution of private property already formally existed in Salta (e.g. the 1853 Argentinian constitution declares the inviolability of private property). However, it is only from the second half of the 1990s that private property became central to accessing land (Mioni et al. 2015). The privatisation of land is accompanied by a process of exclusion of non-owners, a form of accumulation by dispossession (Harvey 2009), which in turn is at the basis of the emergence of wage labour. As noted previously, it is the existence of a market for land and labour, essential factors in social reproduction, which set in motion capitalist dynamics.

Contradictions and centrifugalities

The narrative presented so far has mainly focused on the positive feedback among the various processes, and the centripetal tendency of the system to draw resources and expand. However, our approach openly recognises the existence of centrifugalities (contradictions). From PE we know how every autocatalytic configuration accommodates centrifugal tendencies and negative feedback, both within each autocatalytic loop and/or among competing loops. Here we will focus specifically on the latter, namely the frictions between capital-intensive agriculture and other forms of production. These frictions, which ultimately originate in the competition for limited resources among the various processes, represent important elements of contradictions (centrifugalities)

in the system (Xu et al. 2018). Plainly speaking, the expansion of capital-intensive agriculture draws on a large amount of material (and economic) resources (including land) that are no longer available to support subsistence agriculture (Fig. 4). Similarly, HM (drawing on the dialectical method) recognises the existence of opposing tendencies. The history of capital-intensive agriculture in the Chaco Salteño is not frictionless. These frictions or contradictions emerge at every level (i.e. the material/economic and the cultural/institutional) and reflect the different positions of the various actors with respect to the production and distribution of wealth. In this respect, we maintain that the concept of class antagonism, here intended as a process and as a relation between appropriators and direct producers (Wood 1995b), represents a crucial element of contradiction in the dynamics of the new socio-economic configuration.

Finally, we also note how from a PE perspective, centrifugal tendencies play a crucial role in the dynamics of a complex system in that they provide it with a buffer against dangerous contingencies or with the opportunity to develop and become something else. Similarly, from a HM perspective, contradictions represent leverage points from which to transform the system (Harvey 1997). The resolution of contradictions can either be partial, leading to system adaptation, or total, leading to system transformation (Ollman 2003). Such a distinction resonates with the concept of reformist and transformative change, as presented in the Three Horizons framework (Sharpe et al. 2016). In what follows, we briefly discuss some of the contradictions in the Chaco Salteño by looking at the lower-level and the upper-level spheres separately.

The lower-level sphere

On the material level, the contradictions have expressed themselves in the resistances to the violent or judicial expulsions of many forest users and direct producers (peasants and indigenous peoples) from the lands they occupied for decades, often without title, following the expansion of capital-intensive agriculture in the Chaco Salteño (Buliubasich and Rodríguez 2013; Mioni et al. 2015; Schmidt 2019). This struggle is not over. Capital-intensive agriculture is still competing with alternative land uses and forms of production, which also entail alternative social relationships and social reproduction strategies. For example, in some cases the adoption of silvo-pastoral methods (Tschopp et al. 2020, 2022) or agroecological practices (Sarandon and Marasas 2017) can reconcile the need to sustain the livelihoods of small producers with environmental protection. From the technical point of view, these practices do not require large equipment. In terms of social relationships, the adoption of these practices is strongly supported by peasants' organisations and is based on the cooperation among its members rather than on competition. With respect to reproduction, silvo-pastoral systems and agroecology allow maintaining the tree cover (Peri et al. 2017; Sarandon and Marasas 2017; Betancourt 2020), and are, therefore, compatible also with the indigenous peoples hunting and gathering lifestyle.

The upper-level sphere

The definition of class antagonism as a process implies that it occurs over time "as a pattern in social relations, institutions and values (p. 80)" (Wood 1995b). Such class antagonism manifests itself not only in the material/economic sphere but also in the cultural/institutional sphere. The expansion of capital-intensive agriculture, the associated changes in material/economic processes (technological processes, production processes, social relationships and reproduction) and the way these changes are experienced by the "subalterns" (e.g. the expelled peasants, indigenous peoples) become a terrain of struggle (Gramsci 2014; Crehan 2016). For example, the increasing exposure to pesticide contamination following the expansion of GM soy in Argentina has led to strong contestations in various parts of the country (Lapegna 2016). The material/economic sphere engenders not only "dominant" visions/cultures that reinforce the status quo, but also "critical" ones, that aim at transforming it. Both dominant and critical visions/cultures fight to become hegemonic and establish what Gramsci called "common sense" (Gramsci 2014; Crehan 2016). Although a thorough discussion of Gramsci's contribution is beyond the scope of this article, at this point, it is still worth remarking how "culture" and "common sense", by their effect on institutions and on the material/economic sphere (and ultimately on the biosphere), are real forces of history that must be accounted for. For example, in 2007, the national law for the protection of native forests 26,331/2007 (hereafter referred to as the forest law) was approved by the federal parliament, under the pressure of environmental groups and as a reaction to the high deforestation rates experienced in the previous years, particularly in the Gran Chaco ecoregion (Fernández Milmanda and Garay 2019b, a). However, in this respect some important caveats apply. First, following the promulgation of the national forest law, deforestation peaked in Salta in 2007, prior to the approval of the implementation regulation (Leake et al. 2016). This fact probably was due to the landowners' fears of a strict implementation of the forest law (Seghezzo et al. 2011). Second, following the approval of this regulation in 2008, the effectiveness of the forest law remains uncertain (Nolte et al. 2017; Ceddia and Zepharovich 2017; Volante and Seghezzo 2018; Fernández Milmanda and Garay 2019a) as in Salta significant illegal deforestation has occurred (REDAF 2012). On the one hand, the increase in land prices coupled with the presence

of an organised lobby of large-scale producers in the province of Salta, who successfully shaped the regulation to benefit their interests, explains the weak implementation of the forest law. Similar episodes of capture of the institutional context by organised large-scale agricultural interests have been reported for other parts of the Gran Chaco (Cáceres et al. 2016). On the other hand, the presence of organised movements, bringing together peasants and indigenous people, may also have prevented a far worse outcome. There is indeed evidence that across the whole Argentinian Chaco, organised peasants and indigenous peoples movements played an important role in influencing the implementation of the forest law towards the protection of native forests (Ceddia et al. 2022). Besides the forest law, other examples of institutional reactions include the promulgation of an emergency law suspending all expulsions of the indigenous communities from their land (law 26,160 of 2006, prolonged until November 2025 by laws 26,554/2009, 26,894/2013, 27,400/2017 and decree 805/2021); the decision by the Supreme Court of Justice of Argentina to abrogate the authorisation to deforest given by the government of Salta (Supreme Court of Justice of Argentina 2009); and the 2020 decision of the Inter-American Court of Human Rights (ICHR) to hold Argentina responsible for the violation of indigenous peoples' human rights through its failure to recognise and protect their lands (Inter-American Court of Human Rights 2020). At the same time, there is increasing recognition that the existing capital-intensive agricultural model is environmentally too damaging and could benefit from a reconversion towards agro-ecological approaches (Cotroneo et al. 2021). As recently as August 2020, Argentina established a new national directorate on agroecology within the Ministry of Agriculture (Herszkowicz 2020). With respect to indigenous peoples, various public policies to support their livelihoods exist. For example, the Argentinian Ministry of the Environment finances the USUBI project (in Spanish *uso sustentable de la biodiversidad*) aimed at the sustainable use of biodiversity to enable indigenous communities to develop sustainable management plans for the forest while developing opportunities for the sale of traditional non-timber products (UNDP 2021). Mental conceptions alternative to the profit-oriented one, reflecting a non-utilitarian relationship with nature, are already present in the Chaco ecoregion (Piquer-Rodríguez et al. 2018). In some instances, these mental conceptions also display a stronger sensibility to the need of protecting the forests and its inhabitants (Zepharovich et al. 2020a), an aspect brought more prominently to the fore by the fast pace of deforestation. We do not wish to overstate the importance of such initiatives or claim that they will all be transformative rather than reformist. But, at the same time, they represent seeds of possible transformation (Pereira et al. 2018, 2020). The challenge ahead is to build up a mass movement capable of breaking down the rule of the hegemonic groups (Vanden 2007; Gramsci 2014).

Discussion and outlook on future research

The incipit and the spread of capital-intensive agriculture in the Chaco Salteño can historically be traced back to a significant contingency: the introduction of GM soy in the second half of the 1990s. From that moment on, a series of changes in production methods, social relationships and reproduction, narratives, mental conceptions, and institutions took place, with important social and environmental consequences. These changes have been reinforcing each other in an autocatalytic fashion. At the same time, such changes have also engendered resistances/contradictions at various levels. The historical account presented above strongly emphasises the hierarchical structure of a system organised around a lower-level material/economic sphere and an upper-level cultural/institutional sphere. This allows operationalising in a relatively simple way the SES approach to study the emergence of specific socio-economic configurations and their relationship with the biosphere. Importantly, it is only by considering the dialectical relationship among the six moments underpinning the autocatalysis in the two spheres on the one hand, and the emerging contradictions on the other hand, that a complete picture of capitalist dynamics can be obtained. Our D-SES framework allows opening the socio-economic subsystem and complements existing ones in several ways. For example, a number of general frameworks have been recently developed to guide research in sustainability science (Clark and Harley 2020) and land use science in particular (Aspinall and Staiano 2017; Turner et al. 2020). We note how these frameworks do include most, if not all, the elements discussed in this article, but lack a reflection on the process of emergence that links all the components together. Another prominent framework, the technological transitions one (Geels 2002), explicitly addresses the relationship between technological processes, production processes and the formation of institutions. Yet it does not explicitly look at how technology and production are related to specific types of social relationships (e.g. wage labour versus patronal relationships or non-market exchanges) or social reproduction strategies (e.g. migration towards urban areas). As our case study shows, however, such issues are critical to capitalist dynamics. The SES framework (Ostrom 2009, 2011; McGinnis and Ostrom 2014) in principle acknowledges the relationship between resource uses, users and governance, but it requires a large number of variables and it is essentially a static approach. More dynamic frameworks typically have the disadvantage of either not integrating systematically the different

components of the SES (Anderies et al. 2004; Janssen and Anderies 2013) or of leading to an explosion of the necessary descriptors (Robinson et al. 2017). Our framework based on dialectics and processes explicitly deals with dynamics. At the same time, by considering the relations between the lower-level and upper-level processes within the socio-economic system, our framework offers a comprehensive yet parsimonious description. The World-Earth-System (WES) models (Donges et al. 2018, 2020) partition the overall system dynamics into socio-cultural, socio-metabolic and biophysical taxa, in a way that resembles our distinction between the biosphere, the material/economic sphere and the cultural/institutional sphere. The SES Motif (SESM) framework (Bodin and Tengö 2012) pays particular attention to issues of governance in resource access, thus bringing into focus both the institutional and the social relationship dimensions. However, we feel that both the SESM and the WES framework do not pay particular attention to the role of contradictions/centrifugalities. On a normative level, this implies that these frameworks are often silent on issues of power and injustice, a critique often levied against the SES approach in general (Fabinyi et al. 2014). On the positive level, it means that they cannot fully explain how systems can overcome exogenous shocks by transforming themselves. Our approach neatly incorporates the role of contradictions/centrifugalities, which in the case of capitalist configuration reflects class antagonism. Finally, we would also like to point to some limits of our approach, at least in the way it has been implemented here. By focusing mainly on a single scale, namely the dynamics of agricultural expansion in the Chaco Salteño, we cannot explain how capital-intensive agriculture managed to so easily invade the region. This was possible because the lands in question, even when they were being used and occupied by peasants and indigenous peoples, were private property of landowners (or were privatised public lands). Answering the question of how it all happened would require a reflection on the supremacy the Argentinian state assigns to private property against other rights (e.g. usufruct, common property etc.), a reflection on the role of the state within capitalism that encompasses a larger spatiotemporal scale and that is beyond the remit of this article (Meszaros 2022).

We use the remainder of this section to further interrogate our D-SES framework and briefly elaborate an outlook on future research needs, with a focus on sustainability issues. First, our approach points to the fact that the metabolic relationship between the socio-economic subsystem and the biosphere can be thought of in terms of concatenation of processes. We, therefore, encourage the study of global environmental change by looking at the different sets of interrelated processes that originate it. Such an approach has, for example, been adopted to understand the impacts of urbanisation (Inostroza 2018; Inostroza and Zepp 2021). We also recommend paying particular attention to the presence of contradictions. Our dialectical perspective implies that the capitalist system is not an accomplished entity, but rather it reproduces itself continuously at different scales. Identifying contradictions within this reproduction process is crucial to identify possible ways to overcome the existing system and achieve sustainability (Feola et al. 2021). Second, our approach points to the existence of an upper-level sphere capturing the emergence of culture and institutions. In this respect, our framework facilitates the comparative study of cultural/institutional dynamics. A possible analytical implementation of the D-SES framework could focus on studying how changes in material/economic practices affect the formation of institutions to mitigate the environmental impacts of agricultural expansion. We deployed a preliminary version of the D-SES framework to study the heterogeneous application of the forest law in the twelve provinces of the Argentinian Chaco (Ceddia et al. 2022). A similar approach could be used to study larger geographical areas (e.g. several countries) over a longer time span. Lastly, our approach is based on a system perspective that openly acknowledges issues of complexity. This complexity implies that the system under study is constituted via the interrelation of different processes and across different scales. At the same time, the socio-economic system is constituted also via social relationships. An important corollary of our framework is that the biosphere is not a mere passive fund out of which resources are extracted or a sink where degraded matter and energy can be dumped. Nature is continuously co-produced and co-evolves with the socio-economic system, denoting the unfolding of historical processes (Norgaard 1984; Kallis and Norgaard 2010; Norgaard and Kallis 2011). Recent research shows that humans have been shaping nature for at least 12,000 years (Ellis et al. 2021). For all these reasons, it is important to recognise the existence of a multiplicity of legitimate normative perspectives. Normative questions, which directly ask what sort of nature-economy we want, need to be asked. We see post-normal science (Funtowicz and Ravetz 1993; Funtowicz et al. 1999) as an interesting framework for this type of analysis.

Conclusions

Humans are exerting increasingly strong impacts on the biosphere, interfering with several planetary functions to the extent of pushing them beyond their historical range of variability (Waters et al. 2016). These global environmental changes are happening under the aegis of capitalism, the dominant socio-economic system worldwide. A transition towards sustainability requires a critical understanding of capitalist dynamics (Feola 2020). The SES approach has been developed precisely to study the interrelations between

the socio-economic subsystem and the biosphere, but the most prominent operative frameworks based on the SES approach suffer from some important limitations. First, they treat the socio-economic subsystem as a black box. Second, they fail to capture the specificity of capitalist dynamics, their historical emergence and persistence. Finally, they often remain blind to the existence of contradictions, conflicts and power imbalances (Fabinyi et al. 2014). To tackle these aspects, we develop a dialectical framework to open the socio-economic component of the SES and to provide a systematic historical account of its dynamics. Being based on dialectics, our framework recognises that as a concatenation of processes capitalism is never an accomplished "entity" but it is constantly being reproduced (Holloway 2002). The existence of contradictions, by actively interfering with the reproduction of capitalist dynamics, may lead to the overcoming of capitalist relations. We hope therefore that our framework can do more than elucidate how the system works: the ultimate goal, after all, is to transform it.

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