Merging process ecology and historical materialism to study capitalism dynamics: lessons from Gran Chaco

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Abstract

1. The current pattern of anthropization of the biosphere, which has led scientist to coin the term Anthropocene, cannot be properly understood without accounting for the specific dynamics of capitalism.
2. Here we combine theoretical ecology with a framework from the social sciences, historical materialism, to study these dynamics by looking at the case of capital-intense agriculture in the Gran Chaco. In so doing we espouse a process perspective, and we obtain some important general insights for the transition towards sustainability.
3. We appreciate the interplay between contingencies and autocatalytic configuration of processes in the emergence, persistence and eventually transformation of a socio-economic system.
4. We point to the analogy between the capitalist urge for economic expansion, driven by the competitive search for maximum profits, and the intrinsic growth-enhancing tendency of autocatalytic configurations.
5. More broadly, we expose the dialectical relationship between the set of material/economic processes and cultural/institutional ones, which originates the historical development of capitalist dynamics and the associated pattern of dangerous anthropization.
6. Transition towards sustainability will require acting simultaneously on both spheres, while taking advantage of a suitable window of opportunity.

Keywords: process ecology; historical materialism; complex systems; 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 (Díaz et al., 2019; Steffen et al., 2015). 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 population 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 happen within a capitalist system (Milanovic, 2019), here defined

as a socio-economic system based on private property, wage labour, market exchanges and the competitive search for profits. Such a system 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. 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 the degradation of the Amazon and the boreal forests (Ceddia, 2020; Galaz et al., 2018). For these reasons, the current pattern of anthropization, reflecting the interaction of human society with the environment, cannot be entirely understood without accounting for the specificity of capitalist dynamics. The socio-ecological system (SES) paradigm and the complex adaptive system (Preiser et al., 2018) (CAS) framework appear particularly useful to study how such dynamics first emerged, how they persist and how they can eventually be transformed (see Box 1). Here we operationalize the CAS/SES framework to study patterns of anthropization under capitalism while relying on a specific case study. For this purpose, we combine the theoretical frameworks of process ecology (Ulanowicz, 2019, 2009, 1997) and historical materialism (Marx and Engels, 1970), thus providing a novel way to explore and unpack the dynamics of SES. Additionally, our approach allows integrating historical data on the interaction between humans and nature. This is crucial to understand issues of environmental degradation and to identify appropriate policy interventions (Crumley et al., 2018).We deploy this approach 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, situated in the second largest forest biome in the South American subcontinent (Grau et al., 2015). We also look at possible ways in which this system can be transcended and draw some general conclusions.

Box 1: Complex adaptive systems, socio-ecological systems, hierarchies

At a basic level, a system can be thought of as a group of interacting components, surrounded by an environment with which it may or may not interact (O'Neill et al., 1986). The definition of complexity is somehow less straightforward as it depends on both the number of parts interacting and on the type of interaction. Following (Weinberg, 2001) we can think of systems with a small number of components, which interact in a very organized fashion. In this case,

system dynamics can be described by a set of differential equations. This is the realm of organized simplicity. At the opposite end of the spectrum, we can think of systems with a very large number of components that interact randomly. Here the law of large numbers applies, and system dynamics can be described via statistical approaches. This is the realm of disorganized complexity. Between these two extremes are systems with a not too small number of components that interact in a non-completely random fashion. These medium-number systems cannot be appropriately described neither via differential equations (too many components) nor via statistical approaches (not enough components and not sufficiently random interactions). This is the realm of organized complexity. Complex system theory generally refers to this intermediate type of systems, characterized by the fact that the property of the whole cannot be inferred by the study in isolation of its parts (Bar-yam, 2019; Bar-Yam, 2004). Effectively the properties of the system emerge only when a higher-level perspective (i.e., a system perspective) is adopted. For this reason, complex systems can be thought of as hierarchical structures (Allen and Starr, 2017; O'Neill et al., 1986). The concept of hierarchy is useful as it allows decomposing the overall system into a small number of loosely coupled components (Simon, 1977). Finally, complex systems can adapt to changes (within a certain range) in the external conditions. Among complex adaptive systems, socio-ecological systems indicate those systems which include a human, or socio-economic component, interacting with an ecological or environmental component (Berkes et al., 2000; Preiser et al., 2018).

Process Ecology

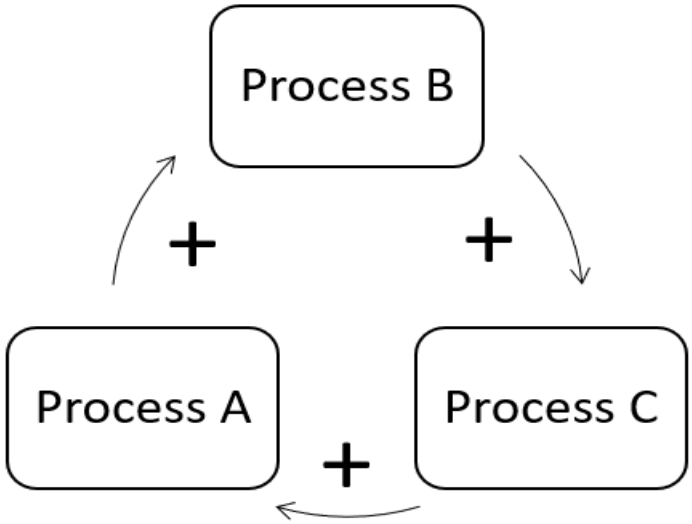
The theory of process ecology is useful to understand how CAS come into being, persist and eventually change or disappear, since CAS constitute themselves relationally, as interactions among processes (Preiser et al., 2018). A process perspective facilitates thinking in terms of emergent phenomena and is particularly apt at integrating the CAS framework to the study of SES (Hertz et al., 2020; Mancilla García et al., 2020). For this reason, the theory can be also deployed to understand the emergence of a particular socio-economic system, including the capitalist system in general and capital-intensive agriculture. We define 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) (p. 29)". This definition provides some essential insights. First, it acknowledges the role of chance or, more broadly, contingency. Second, it hints at the fact that order is imparted to contingent events via a set of constraints. Thirdly, it posits that the outcome of a process, unlike a law, is non-random but still

indeterminate. CAS tend towards increasing organization (i.e., development), but contingency and indeterminacy remain crucial and point to the openness in the causal fabric. The three principles of process ecology, can now be enunciated as follows (Ulanowicz, 2009):

1. Contingency: any system is vulnerable to disruption by external events. Contingency range from simple, repeatable events, to unique events, to conditional probabilities (Ulanowicz, 2019). For our purposes, we define an event as a contingency if it is independent from the system of interest (Lewontin and Levins, 2007). In general, the existence of contingencies provides the opportunity for radical change to happen.
2. Autopoiesis: a process, via the intermediation of other processes, can influence itself. A concatenation of processes can play a powerful role in the emergence of organization and structure. Of interest here, is a certain type of positive feedbacks, referred to as autocatalytic loops. In this configuration, each process/node in the loop promotes/enhances the subsequent process/node, thus acting in mutualist fashion. Autocatalytic loops present a number of interesting properties (see Box 2), which make them growth-enhancing (Ulanowicz, 1997). Such properties are an emergent feature of the entire loop, rather than of the individual processes making it up. In this sense they reflect the existence of a hierarchical structure (as mentioned in Box 1). Example of autocatalytic loops range from the diffusion of technologies when increasing returns to adoption exist, to the evolution of an entire economic system (Arthur, 2014; Schreyögg and Sydow, 2011). Autocatalytic loops, to sum up, provide us with a conceptual tool to understand the emergence of complex organized systems and their persistence.
3. History: systems differ from one another according to their history, some of which is recorded in their material configuration. The emergence of a certain autocatalytic loop 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. The system becomes locked-in a certain path and the accidental small event that led to its emergence is not easily forgotten (Arthur, 2014). In a certain sense, systems do have a memory (Nyström and Folke, 2001) and history, here intended as irreversibility, does matter. Part of this history can be observed by looking at the material configuration of the system itself. This last remark turns out to be of crucial importance for the purpose of this paper, as discussed in the next section.

Box 2: Autocatalytic loops and their properties

Autocatalytic loops (Box 2 Figure) present a number of interesting properties including centripetality, directionality and autonomy which, by constraining the behaviour of their components, make them inherently growth-enhancing (Ulanowicz, 1997; Xu et al., 2018).



Box 2 Figure | Autocatalytic loop. The formation of an autocatalytic loop, as a concatenation of positive feedback (→ +), also offers the opportunity to reflect on causality in CAS. For example, if one were to take only a part of the system into consideration (say Process A →+ Process B), then a clear cause-effect relationship could be inferred. Yet, once the whole loop is considered, establishing such a linear causal relationship becomes certainly problematic(Ulanowicz, 2009). In fact, one can easily say that each process is at the same time a cause and an effect. The relationship is dialectical.

The first property, *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). The second property, *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 (denoting a lower level in a hierarchical structure), constraining their behaviour and favouring those that are most beneficial to the whole loop. The third property, *autonomy*, refers to the fact that such a selective pressure emerges at the loop level (denoting the upper level in a hierarchical structure) and is not obviously attributable to any individual component of the loop. A few additional caveats are worth making. Besides the growth-enhancing effect of centripetality, there are also some opposing tendencies, which can be thought of as

centrifugality (Xu et al., 2018). First, although during its development an autocatalytic loop tends to become increasingly organized, its persistence requires that a certain level of disorganization/redundancy is maintained, in order to avoid brittleness. Second, during the development phase, the autocatalytic configuration can come across a new node, which could 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 additionally 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 as a balance between opposing tendencies.

We conclude this section by restating the link between process ecology, CAS/SES and hierarchy theory. A feature of CAS is their hierarchical organization. Such organization is compatible with the emergent properties of autocatalytic configurations. The emergent structure of a CAS (i.e., the overall loop in Box 2 Figure) represents the upper hierarchical level and acts as a constraint to the dynamics of the lower levels (i.e., the individual processes making the loop in Box 2 Figure). The effect of a disruptive contingency implies the disappearance of the system structure (i.e., the upper level constraints). For this reason, behaviour becomes erratic as the system dynamics are now dominated by the lower level processes. The system may stabilise when a new structure emerges, that is when new upper level constraints are found.

Historical Materialism

Historical materialism, as a framework to study the emergence of a particular socio-economic system, is associated to the work of Friedrich Engels and Karl Marx. It posits that cultural and institutional structures emerge from the material aspects of life. Once the obvious fact that cultural and institutional structures themselves constrain the material aspects of life is considered, the features of an autocatalytic configurations appear. Superimposing autocatalysis to historical materialism, is appropriate since the latter relies on the dialectical method (Engels, 1892). Dialectics, as posited by Heraclitus and the ancient Greek philosophers first and by

Hegel later, sees reality, nature, and history as a concatenation of processes, thus becoming. "Dialectics […] comprehends things and their representations, ideas, in their essential connection, concatenation, motion, origin and ending […] Nature is the proof of dialectics (Engels, 1892, p. 34) (p. 34)". For this reason, dialectics resonates with process ecology.

The dialectical approach adopted by Marx in his historical materialist analysis is often evident in some passages which sound "ecological". For example, concerning capitalism he writes "This organic system itself, as a totality, has its presuppositions, and its development to its totality consists precisely of subordinating all elements of society to itself, or in creating out of it the organs which it still lacks. This is historically how it becomes a totality (Marx, 1993, p. 278) (p. 278)". Through the lenses of process ecology we can detect in this passage a connection with autocatalysis and with its key properties of centripetality (i.e., a system which continuously develops its own preconditions) emergence (i.e., the system has its presuppositions) and constraint (i.e., the systems tends to subordinate all elements of society to itself). At this point an important caveat is worth making. Besides its inherent centripetal (i.e., growth enhancing) tendencies, the development of the capitalist system, according to the dialectical approach taken by Marx, is not free of contradictions or opposing tendencies, in a way that resonates with the presence of centrifugal tendencies in autocatalytic configurations. This is a consequence of the dialectical method developed by Marx and it is expressed very clearly in the following passage "In its rational form [dialectics, ndr] (…) it includes in its positive understanding of what exists a simultaneous recognition of its negation, its inevitable destruction; because it regards every historically developed form as being in a fluid state, in motion, and therefore grasps its transient aspect as well. The fact that the movement of capitalist society is full of contradiction impresses itself most strikingly on the practical bourgeois in the changes of the periodic cycle through which modern industry passes, the summit of which is the general crisis (Marx, 1990a, p.103) (p. 103)".

Additionally, recent advances in Marxist scholarship show how the tension between capitalism and nature, the "irreparable rift in the interdependent process between social metabolism and natural metabolism (Marx, 1990b) (p. 949)", is a central theme in Marx and Engels' thought (Foster, 2000; Saito, 2017). According to these interpretations of Marx and Engels' work, the "metabolic relationship with nature" is the result of the historical (here intended as inherently social) and material (including necessarily nature) conditions under which society operates. Therefore, the historical material conditions include both matter/nature and social/historical relationships, in a way which resonates with the modern definition of SES (Preiser et al., 2018).

This understanding has generated a rich literature on social metabolism (Fischer-Kowalski, 1998).

To sum up, by combining historical materialism with process ecology, the emergence of any socio-economic system, including the capitalist system, with its specific pattern of anthropization, can be thought of as the formation of an autocatalytic loop. In this case, what are the various processes in the loop? In another passage, from the first volume of *Capital*, Marx discusses the role of technological development and 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)". This is an important passage, which requires careful analysis. According to historical materialism the metabolic relationship between man and nature is a feature of the human condition in general, and it is therefore transhistorical. Moreover, such a relationship is always mediated by technology. It is in this sense that technology reveals the active relation of man to nature. This fact can be clearly appreciated by reflecting on the myth of Prometheus (Aeschylus, 1832). However, the specific form the metabolic relationship with nature takes at a certain point in time, is the result of historical/social practices, always mediated by technology, which depend on the specific configuration of the socio-economic system. Technology is important because it affects social practices, which include not only production per-se, but also, social reproduction, the way of thinking and so forth. A further elaboration of the above passage allows identifying five "moments" (or processes/nodes) of the total autocatalytic loop characterizing the metabolic relationship with nature as mediated by technology. These moments can be studied to understand capitalist dynamics. They are: social relations, mode of material production, daily life and social reproduction (i.e., material/economic processes), development of mental conceptions and institutional frameworks (i.e., cultural/institutional processes) (Harvey, 2017). Moreover, according to Marx cultural/institutional processes emerge from material/economic ones (see Box 3). We can therefore think of the former set of processes forming a "faster" loop and the latter a "slower" loop. As already noted, we find it obvious that cultural/institutional processes also constrain material/economic processes, thus originating an autocatalysis. In any socio-economic system each one of these processes/nodes affect and reinforces the other processes/nodes in a way that is beneficial to the whole loop. The specific relationship of human societies to nature according to the historical materialist approach, is the result of the configuration of these five processes and their interactions. Such a configuration, can be conceptualised in autocatalytic fashion as

a non-nested hierarchy (Allen and Starr, 2017), where fast processes (material/economic) lead to the emergence of slow processes (cultural/institutional), which in turn exert a constrain on the former (Figure 1).

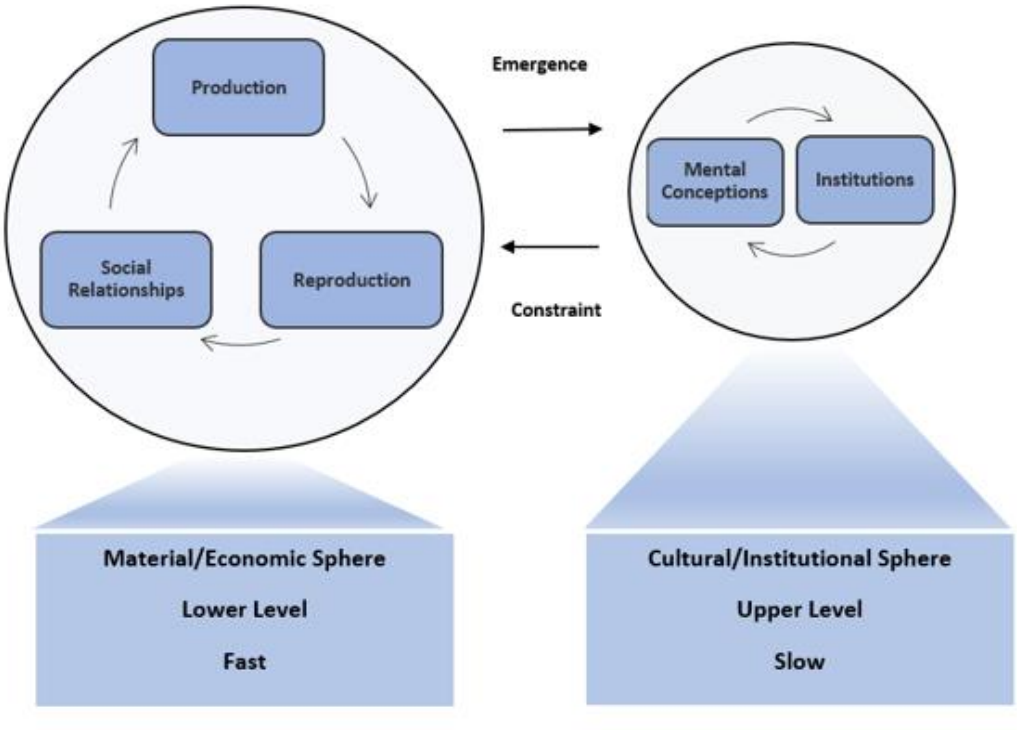


Figure 1| Heuristic representation of the metabolic relationship with nature as mediated by technology. According to historical materialism, the metabolic relationship with nature is a condition of human existence. Such a relationship follows from the dialectical interaction between the material/economic sphere (which itself comprises the interaction among 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 (see Box 2). It goes without saying that the slower/upper level (i.e., the cultural/institutional sphere) constrains the faster/lower level (i.e., the material/economic sphere). The whole configuration can be thought of as an autocatalytic loop and a non-nested hierarchy (Allen and Starr, 2017).

By explicitly spelling out the five moments, which define the metabolic relationship with nature, an approach combining process ecology and historical materialism allows capturing the unfolding of the historical process and the emergence of capitalist dynamics within a CAS.

Box 3: The metabolic relationship to nature and the interaction among the material/economic and cultural/institutional spheres.

According to historical materialism, the relationship of man to nature (i.e., the metabolic relationship) is a constant of human existence and is mediated by technology. The specific metabolic relationship to nature under capitalism, and the specific technological organization, is the result of the particular configuration of the autocatalytic loop associated to it. Moreover, the relationship between the five constituent moments (nodes/processes) of the entire loop (i.e., production, reproduction, social relationships, mental conceptions, institutions) is likely to occur at different speeds. It becomes then important to distinguish slow from fast interactions. In this respect the following passages from another work by Marx and Engels, *The German Ideology*, are quite helpful "The first historical act is thus the production of the means to satisfy these needs, the production of material life itself…the second point is that the satisfaction of the first need, the action of satisfying and the instrument of satisfaction which has been acquired, leads to new needs… the third circumstance which, from the very outset enters into historical development, is that men, who daily re-create their own life, begin to make other men, to propagate their kind… the production of life, both of one's own labour and of fresh life in procreation, now appears as a twofold relation: on the one hand as a natural, on the other hand as a social relation…It follows from this that a certain mode of production….is always combined with a certain mode of co-operation…Only now, after having considered four moments, four aspects of primary historical relations, do we find that man also possesses consciousness (Marx and Engels, 1998) (pp. 48-49)". In these passages, the authors maintain that the starting point for understanding the metabolic relationship with nature and its technological configuration, is the interaction between the nodes/processes of modes of production, modes of reproduction and social relations. The interaction among these processes, leads to the emergence of and interacts with the remaining moments/processes, which include the formation of mental conceptions and institutions. This follows from a passage where Marx states "My view is that each particular mode of production, and the relation of production corresponding to it at each given moment, in short the 'economic structure of society' is the 'real foundation on which arises a legal and political superstructure and to which correspond definite forms of social consciousness' and that 'the mode of production of material life' conditions the general process of social, political and intellectual life (Marx, 1990a) (p. 175)". Since Marx states that the economic structure "conditions" the institutional superstructure

(rather than determining it), his approach does not contradict process ecology, which is non-deterministic and allows for indeterminacy.

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

We will now deploy our approach to study the appearance of capital-intensive agriculture in the Chaco Salteño (Figure 2) and the consequent anthropization pattern.

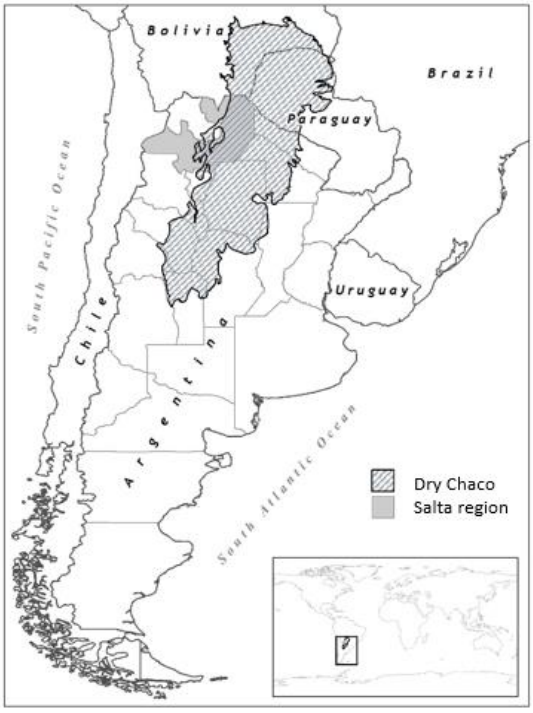


Figure 2| The Dry Chaco and the Chaco Salteño region. The Gran Chaco, with an extension of over 1 million hectares across Argentina, Bolivia, Paraguay and Brazil, is the second largest forest biome in South America after the Amazon (The Nature Conservancy, 2005). The Gran Chaco is divided into two ecoregions: the Humid Chaco (East) and the Dry Chaco (West). The latter extends for about 790,000 Km^2 mainly situated in Argentina. We will focus on the portion of the Dry Chaco located in the province of Salta, known as Chaco Salteño.

The choice of this case study is based on three reasons. First, the whole Gran Chaco has experienced high deforestation rates over the period 1990-2010 due to the expansion of capital-intensive agriculture, namely soybean and the consequent displacement of cattle ranging towards the interior of the Chaco (Fehlenberg et al., 2017). The province of Salta recorded a peak in deforestation over the period 2002-2009, with annual rates estimated at over 2% p.a.,

a fact that has led to the emergence of strong social conflicts over land use (Vallejos et al., 2020). The region provides an extremely useful case to analyse the process of anthropization under capitalist conditions. We openly acknowledge that the Chaco Salteño is part of a larger system (i.e., the South-American continent), while we maintain that the choice of the boundaries are to some extent always arbitrary and reflect the purpose of the investigation (Cilliers, 2001). Second, the large-scale expansion of capital-intensive agriculture in the region is a relatively recent phenomenon, which started in the second half of the 1990s, thus making recollecting its history easier. The anthropization of the Chaco Salteño largely precedes the emergence of capital-intensive agriculture (see SI) (Iriondo, 2006). However, prior to the widespread introduction of capital-intensive agriculture, the land use system in the Chaco Salteño revolved mainly around extensive livestock ranging by peasants and hunting-fishing-gathering activities by indigenous peoples. This extensive and subsistence production system, typical of the whole Gran Chaco region, relied on the presence of native forests for the provision of fodder trees, shrubs and grasses for cattle, horses and goats (Cáceres et al., 2016). On the contrary, capital-intensive agricultural entailed the removal of forest cover and significantly altered the pattern of anthropization with important environmental and social consequences (Fehlenberg et al., 2017). That is to say, the Chaco Salteño remains relatively marginal in the context of capitalist agriculture. It is only from the second half of 1990s onwards, with the arrival of capital-intensive agriculture, that the situation changes dramatically, with important environmental and social consequences. Third, in spite of its peculiarities, the pattern of anthropization under capital-intensive agriculture in the Chaco Salteño presents sufficient analogies with other recorded cases (Li, 2014), to allow drawing some general insights.

To sum up, we will describe the history of the material configuration associated with the formation of capital-intensive agriculture and the consequent displacement of the previous extensive/subsistence agriculture. We will look at these processes as the emergence of an autocatalysis among the various moments (nodes) above mentioned (Figure 3).

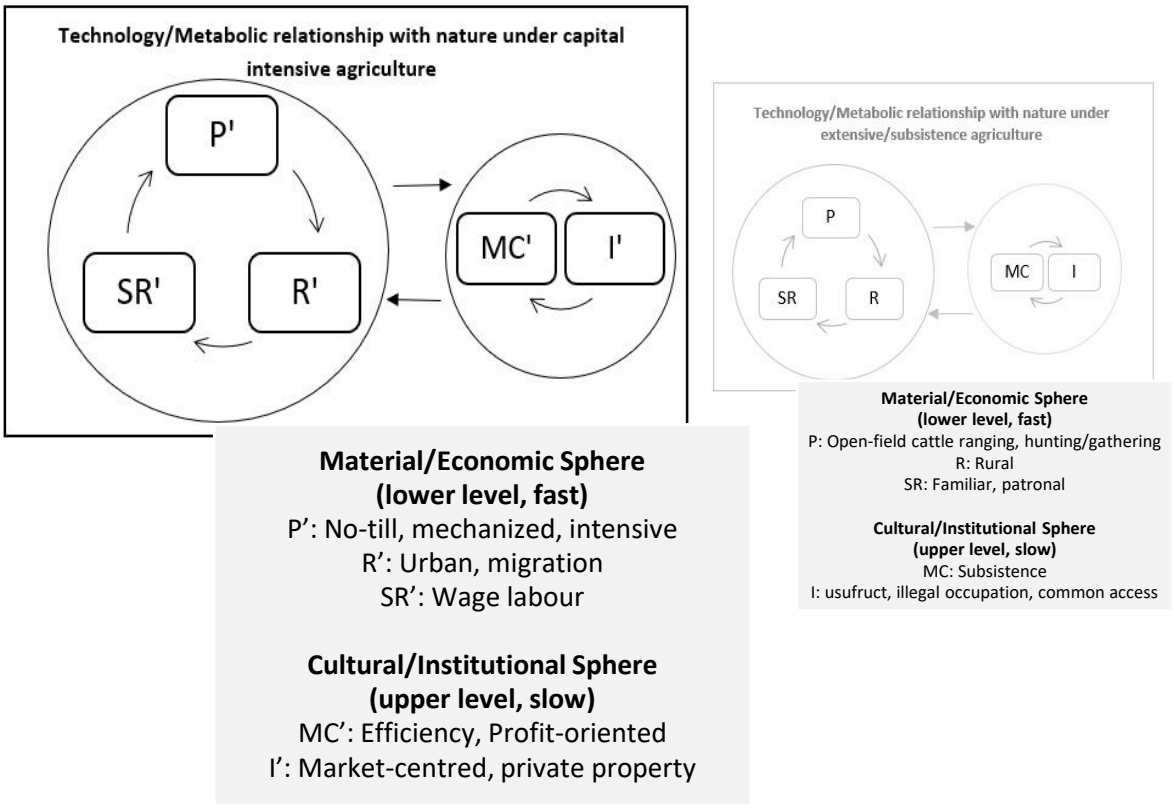


Figure 3| The regime shift from extensive/subsistence land use to capital intensive land use. The figure portrays the displacement of the old land use regime by the new land use regime. The old regime was characterized by the old material/economic sphere (which included the old mode of production P, the old reproduction R and the old social relationships SR) and by the old cultural/institutional sphere (which included the old mental conceptions MC and the old institutions I). The new regime is characterized by the new material/economic sphere (which includes the new mode of production P', the new mode of reproduction R' and the new social relationships SR') and by the new cultural/institutional sphere (which includes the new mental conceptions MC' and the new institutions I').

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

According to the first principle of process ecology, any system is vulnerable to disruption by external contingent events. In the Chaco Salteño, the crucial event which led to the displacement of the old extensive and subsistence land use, is the introduction of genetically modified herbicide tolerant soy (GM soy hereafter). Before providing a brief historical account, a caveat on the opportunity of considering the introduction of GM soy as a contingency should be presented. From the limited perspective of the Chaco Salteño, the arrival of GM soy can be treated as an exogenous shock, thus in line with our definition of contingency. Although some

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, with the resolution 167 of the Secretary of Agriculture, Fishing and Food, authorizes the commercial growing of GM soy. The crop expanded first in the pampean region but very quickly reaches also the extra-pampean regions, including the Chaco Salteño. These developments mark the spread of capital-intensive agricultural production and the concomitant expulsion and marginalization of both peasants and indigenous peoples from lands they have been occupying for long periods (Mioni et al., 2015). Through a hierarchy perspective of CAS, the GM soy contingency brought up significant changes in the material/economic sphere that disrupted the existing cultural/institutional constraints. We examine this process more in detail in the following subsections.

Finally, we note that the importance of the GM crop technology for the change in the anthropization process does not imply technological determinism. This aspect is relevant since openness and indeterminacy are key features of CAS/SES. The introduction of GM soy in the region of study should therefore be considered a significant event, marking a shift in the socio-technical regimes, with implications for institutions, culture and symbolic meanings (Geels, 2002).

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

The second principle of process ecology posits that a process, via other processes can influence itself. We therefore study the concatenation of processes, since the introduction of GM soy, constituting the emergence of capital-intensive agriculture as an autocatalysis. We focus first on the fast loop, the material/economic sphere (i.e., the effect GM soy on modes of production, reproduction and social relationships) and subsequently on the slower loop, the cultural/institutional sphere (i.e., the effects on mental conceptions and institutions).

The fast loop: modes of production, social relationships, and reproduction

The use of GM soy allowed reliance on no-till systems, which in turn enabled the growing of the crop in areas with relatively little water (rain or underground), like the Chaco Salteño. The technological innovation was accompanied by managerial/organizational innovation, the most significant of which is the leasing of land and sub-contracting of most of the agricultural operations (Cáceres, 2015; Colina et al., 2012). More recent developments include the introduction of value-adding activities, by coupling soy production with the rearing of livestock

in feedlot systems (Cáceres and Gras, 2020; Gasparri and de Waroux, 2015). Overall, this new agricultural production method is geared towards the generation of both profits for the private investors and foreign currency for the national economy. The GM soy technology 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). Effectively land provided the physical space where the existing capital (including financial resources and machineries), always in search of the best return, could be deployed to generate an income flow and pursue further accumulation (Fairbairn, 2020). In this sense, the expansion of the agricultural frontier can be described as a spatio-temporal fix (Harvey, 1999), where environmental degradation is a by-product of this process.

The change in the modes of production and the modification in the natural environment, associated with the expansion of capital-intensive agriculture in the region and the consequent expulsion of indigenous peoples and peasants, has important consequences on the patterns of social relationships, which become increasingly centred around market transactions (Wood, 2002). As already noted by Polanyi, social relationships become incorporated into market exchange relations (Polanyi, 2001). This point cannot be stressed enough. The market becomes not a mere opportunity but 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). When the market becomes central not only to selling the output, but also to accessing land and labour, efficiency and profit maximisation become an imperative thus impairing the social and cultural reproduction of peasants and indigenous peoples (Barraclough and Ghimire, 1995). This process further reinforces the spread of the capital-intensive mode of production, alongside the narrative that "there is no alternative" to development. The penetration of capitalist logic into the reproductive sphere of peasants and indigenous communities, known as commodification of agriculture, has been a central theme of rural studies in recent decades (Bernstein, 2017). For example, in the Chaco Salteño, as in other parts of the region, the peasants and indigenous peoples economy formerly relied on the work of family members or on the performance of small casual jobs (changas), usually within a patron-client relationship (Blaser, 2010; Wolf, 2013). These forms of production entail a kind of social relationships that are essentially personal and non-contractual. Under capital-intensive agriculture this type of social relationships are substituted by wage labour contracts (Garay et al., 2017). The limited job opportunities, alongside with the expulsions, lead to the migration of peasants and indigenous

peoples towards urban areas, where they often live under extreme poverty. Between 1991-2001, in the province of Salta alone, migration from rural to urban area led to an average increase in urban population of almost 32% (Schmidt, 2014). In the Chaco Salteño ecoregion, which only covers a part of the Salta province, the urbanization of indigenous peoples increased significantly from 48% to 58.8% over 2001-2010 (Klarik, 2019).

The slow loop: mental conceptions and institutions

The diffusion of capital-intensive agriculture, based on the extensive adoption of GM soy, has generated not only a reorganization of agricultural production, forms of social reproduction and social relationships, but also an important shift in the mental conceptions. It has already been noted that technology is not neutral and has the ability to produce new worlds both around and within us (Arthur, 2009). This fact is openly acknowledged by the socio-technical transition approach, which points to the key interactions between technological change and cultural and institutional shifts (Geels, 2002; Geels et al., 2017). New technologies "alter the things we think about…and the things with which we think (Postman, 2011) (p. 20)". In particular, the expansion of capital-intensive agriculture, goes hand in hand with the diffusion of a dominant narrative grounded on the concept of efficiency, productivity and economic development based on free market competition and profit maximisation (Gras and Cáceres, 2020), further accelerating the expansion of the capital-intensive agricultural model. If, to a man with a hammer everything looks like a nail, one could paraphrase that in the Chaco Salteño, to a man with GM soy all the land looked like a soy field: an excellent investment opportunity. 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 (Mioni et al., 2015). Deforestation and requests for land clearing peaked in 2007 (Leake et al., 2016). This in turn, brought about two important institutional changes, which deserve further scrutiny.

The first one, relates to the reactivation of the land market and the role of private property. The increase in the value of the land in the region, following the arrival of capital-intensive agriculture, initiated a process of land reclaim on the part of their legal owners and the expulsion of both peasants and indigenous peoples. In effect, legal ownership, intended as full individual alienable property right, mediated by the mechanism of the market, became the privileged mode of accessing land at the expense of all other forms (e.g., usufruct, possession, illegal occupation etc.). Although the institution of private property already formally existed (e.g., the 1853 Argentinian constitutions declares the inviolability of private property; the civil code in Argentina dates to 1871, while the civil procedural code of the province of Salta dates

to 1978), it becomes central to accessing land only from the second half of 1990s (Mioni et al., 2015). This can be thought of as a process of transposition (i.e., the institute of private property gets transposed to a new context, namely land access and use in the Chaco Salteño) and re-functionality (i.e., the transposition generates radical new uses of the land) (Padgett and Powell, 2012). The second one, relates to the capture of the institutions to protect the remaining forests. In 2007 the national law for the protection of native forests 26331/2007 (from now on simply forest law) is 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, 2019a, 2019b). Although the province of Salta was the first in Argentina to pass the implementation regulations of the forest law in 2008, it has been noted how such regulations presented a low level of consistency with the national forest law and they have been poorly enforced (Fernández Milmanda and Garay, 2019a). The presence of an organized lobby of large-scale producers in the province of Salta, who successfully shaped the regulation to benefit their interests, explains the questionable effectiveness of the forest. Similar episodes of capture of the institutional context by organized large-scale agricultural interests have been reported for other parts of the Gran Chaco (Cáceres et al., 2016).

Imagining a possible transformation towards sustainability

The incipit and the spread of capital-intensive agriculture in the Chaco Salteño can historically be traced back to the introduction of an important technological innovation, namely GM soy, in the second half of 1990s. From that moment on, a series of changes in production methods, social relationships and reproduction, narratives, mental conceptions, and institutions took place. Although the changes have not always been smooth, overall, the different processes/nodes described in the previous section, have been reinforcing each other in an autocatalytic fashion. As a result, a new regime of land use, strongly based on the competitive search for maximum profits, on private property and production for the market has rapidly supplanted the previous one, based on subsistence production. The expansion of the new capital-intensive agricultural regime draws a growing amount of resources towards it, thus exhibiting the centripetality typical of autocatalytic configurations. For example, the cultivation of GM soy in the Chaco Salteño, relies heavily on the use of external agricultural inputs (e.g., glyphosate, machinery), financial resources and skilled labour (Cáceres, 2015). At the same time, the emergence of new organizational forms better able to cope with the new production methods, the establishment of a strong narrative centred around private property,

profits, and competitiveness and its influence on the institutional context, reflect a process of qualitative development of the new regime. In this process, capital-intensive agriculture is "subordinating all elements of society to itself, or in creating out of it the organs which it still lacks (Marx, 1993) (p. 278)". Such a development involves the selection of certain processes (that are functional to capital-intensive agriculture) against other processes (which are not functional). Escaping the dynamics of such a regime, becomes increasingly difficult.

Given these premises, we would like to make some preliminary considerations on whether and how a transformation towards a new regime, less detrimental to the environment and better capable of meeting the needs of peasants and indigenous communities, is possible. In order to address this question, the first step is to imagine what such a possibility would look like (Feola, 2019). It is important to reflect on possible triggers of change, on the ability of the current system to adapt to such triggers or to succumb and transform (see Box 4) (Folke et al., 2010), and on what the seeds of a new autocatalytic configuration could be.

Box 4: Transformation as multi-phase and multi-level processes

In the SES literature, transformability is defined as the ability of a system to radically change its configuration in the face of shocks that make the current structure untenable (Folke et al., 2010; Walker et al., 2004). System's transformation is conceptualised as multiphase processes. In the first phase, preparation, new systems configurations are explored. In the second phase, navigation, the turbulence associated with the transition from the old to the new configuration must be managed (Olsson et al., 2008). In the third phase, stabilisation, the new configuration has to be "institutionalised" (Moore et al., 2014; Olsson et al., 2006, 2004). The preparation and the navigation phase are connected by a window of opportunity, usually associated to a shock or crisis that destabilises the old system. The issue of transformation has been widely discussed also in the socio-technical transition literature, where the process is conceived as the result of dynamical interactions across three nested levels: the landscape (i.e., the social-environmental background), the regime (i.e., the current configuration of dominant actors) and the niche (i.e., free spaces of experimentation outside the regime) (Geels, 2002; Geels et al., 2017). According to this literature regime shifts can occur as a result of a change in the landscape, representing an exogenous shock or a crisis, that allows the practices developed in the niche to become dominant. Recently, the compatibility between the two strands of literature

has been openly acknowledged, whereas transformative processes can be thought of as simultaneously multi-phase and multi-level (Herrfahrdt-Pähle et al., 2020).

In a sense, the transformability of a system, its ability to become something different, is negatively related to its resilience. Resilience, *sensu* Holling, is defined as the ability of a system to maintain its structural configuration, develop and adapt in the face of shocks (Holling, 1973). Connectivity and diversity (among the various parts of a CAS) have been shown to be two key properties that affect a system's resilience: a CAS made of homogenous hyperconnected parts is likely to be brittle (Holling, 1986; Nyström et al., 2019). In the case of capital-intensive agriculture, its homogeneity can be inferred from the preference for monocultures and highly standardised production methods more in general, while its high degree of connectivity can be inferred by its strong dependence on global markets for standardized inputs, for financial capital and for the sale of commodities. As a system develops and increases its level of organization, it tends to become less resilient. Under these circumstances, it is from the "reservoir of sundry and unfit processes that [….] the system draws to create an adaptive response to the new threat(Ulanowicz, 1997) (p. 92)". The pursuit of increasing levels of efficiency and organization, in this sense, jeopardises the ability of the system to adapt and respond to unusual perturbations.

Chance as a trigger of change

The first principle of process ecology states that every system is susceptible to disruption by external contingencies. Environmental or social disruptions can be powerful triggers of change (Herrfahrdt-Pähle et al., 2020). At the moment of writing, one of such critical events is the COVID-19 outbreak. Ironically, although from the limited perspective of the Chaco Salteño the outbreak can be considered as an exogenous chance event, on a broader scale agricultural expansion and deforestation have been indicated as important drivers behind the emergence of COVID-19 and other zoonotic diseases (Rulli et al., 2020). The current pandemic represents a significant shock for the whole global economy, with implications also for the production and trade of agricultural commodities. Overall, the outlook for agricultural commodity production remains characterised by high levels of uncertainty and reduced profitability (World Bank Group, 2020). In the case of capital-intensive agriculture in the Chaco Salteño, the system shows already signs of distress. Environmental degradation (e.g., loss of soil fertility,

widespread appearance of herbicide resistant weeds) and socio-cultural displacement (e.g., eviction and exclusion of peasants and indigenous communities) are affecting the profitability of capital-intensive agriculture in the region, while at the same time generating social responses in the forms of conflicts over the right to access land (Cáceres and Gras, 2020). Using the transformability language, the outbreak represents a change in the landscape and could provide a window of opportunity for a new system to emerge.

Autopoiesis and the seeds of change

The occurrence of an exogenous shock can certainly facilitate system transformation, by providing a window of opportunity. However, transformation requires also the existence of "seeds of change", intended as real-world processes that are currently marginal but have the potential to grow in impact (Bennett et al., 2016). These seeds not only need to be nurtured, but they also require a process of institutionalization that stabilises the new configuration (see Box 4). By referring to the hierarchical configuration presented in figure 1, this implies that transformation require action on both the material/economic sphere (i.e., the lower level) and on the cultural/institutional sphere (the upper level).

The second principle of process ecology states that a process, via other processes can influence itself. In our context, it is therefore important to identify which set of processes could form the basis of a new autocatalytic configuration, alternative to capital-intensive agriculture. Should the COVID-19 crises prove to be fatal to the current regime, what are the nodes/ processes that could lead to the emergence of a new regime, with a different metabolic relation to nature? The narrative presented so far has mainly focused on the positive feedback among the various processes, and the centripetal tendency of the system to expand. However, the history of capital-intensive agriculture in the Chaco Salteño is not free from contradictions and resistance, denoting the existence of centrifugal tendencies. Indeed, these episodes of resistance could represent the seeds of a future system. In what follows, we briefly discuss some of these episodes. We are not so naïve to believe that change is easy or necessarily for the better. Yet identifying where the potential for the emergence of a new system lies is important to foster change. We briefly discuss this potential, by focusing separately on the fast loop (i.e., material/economic sphere) and the slow loop (i.e., cultural/institutional sphere).

The fast loop

With respect to production methods, we would like to note how silvo-pastoral-systems are emerging as an important way of reconciling the needs of small-scale producers and peasants' communities with the necessity of lowering environmental impacts in the region. The adoption

of silvo-pastoral methods, oriented more towards sustaining the livelihood of small producers rather than profits, is strongly supported by peasants' organizations and based on the cooperation among its members rather than on competition (Tschopp et al., 2020). At the same time, there is increasing recognition that the existing capital-intensive agricultural model is unsustainable and could benefit from a reconversion towards agro-ecological approaches. As recently as August 2020, a new national directorate on agroecology has been created within the Ministry of Agriculture. Both silvo-pastoral systems and agroecology require small economic investments, promote the diversification of income sources, allow maintaining the tree cover (Betancourt, 2020; Peri et al., 2017; Sarandon and Marasas, 2017), and are therefore more compatible also with the indigenous peoples hunting and gathering lifestyle. With respect to indigenous peoples, various public initiatives are being introduced. For example, the initiative about the sustainable use of biodiversity aims at enabling indigenous communities to develop sustainable management plans for the forest while developing opportunities for the sale of traditional non-timber products.

The slow loop

With respect to the slower processes, some important signals can be detected in the institutional context. The case of the 2007 forest law, already mentioned, can be clearly ascribed to an episode of resistance against the expansion of the capital-intensive agriculture (even though its implementation has subsequently been captured by the agribusiness interests). In 2006 the federal parliament promulgated the law 26,160 (prolonged until 2021 with laws 26,554/2009, 26894/2013 and 27,400/2017), declaring the state of emergency in which indigenous communities live and suspending all the processes of expulsion of the communities from their land. Analogously, in 2010 the province of Salta approves the law 7,658 to initiate a process of tenure regularization for peasants. In 2009, the Supreme Court of Justice of Argentina has suspended and abrogated the authorization to deforest given by the government of Salta (Supreme Court of Justice of Argentina, 2009). In February 2020, the Inter-American Court of Human Rights (ICHR) has held 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). The ruling is particularly significant as the dispute involves the state and the indigenous communities, represented by the Lhaka Honhat (literally meaning Our Land) association, and peasants families, represented by the Organization of Creole Families (OFC) located in the north of the province of Salta. At the moment of writing, the Argentinian national parliament is discussing a proposal to reform the existing forest law that would completely

forbid any further deforestation. Mental conceptions alternative to the profit-oriented one, reflecting a non-utilitarian relationship with nature and a stronger sensibility to the need of protecting the forests and its inhabitants, already exist in the Chaco ecoregion (Zepharovich et al., 2020).

The role of agency

The current crisis of the capital-intensive mode of production, alongside the mentioned institutional shifts, could promote the affirmation of more environmental and socially benign forms of agriculture in the region. However, the emergence of a new autocatalytic configuration, reflecting a transformation towards a more sustainable system, is not automatic. Instead the openness in the causal fabric suggests that besides chance, human agency plays an important role (Herrfahrdt-Pähle et al., 2020). In this respect, "institutional entrepreneurs" who are able to establish connections across the various processes, and across the different levels, while instigating collective action is also important (Ingold and Christopoulos, 2015; Westley et al., 2013). Although a complete treatment of this aspect would require a separate article, we would like to note how a number of figures in the Chaco Salteño fill in this role. The indigenous organization Lhaka Honhat, its leader Francisco Perez and the non-governmental organization Asociana played a pivotal role in the ICHR case. Peasant organizations like Union y Progreso, alongside networks of organizations like Redes Chaco (www.redeschaco.org) have been instrumental in advancing the rights to land of peasants, while also promoting the adoption of more environmentally benign production methods.

Conclusions

Humans are exerting increasingly strong impacts on the biosphere, a fact that has led scientist to coin the term Anthropocene, to denote the era, began with the industrial revolution, in which human activities impact on planetary functions to the extent of pushing them beyond their historical range of variability (Waters et al., 2016). To slow down and possibly reverse this trend, it is necessary to first understand how it developed. To this end, we combine process ecology with historical materialism and study the emergence of capital-intensive agriculture in the Chaco Salteño. This approach allows us to distil some general insights. First, we appreciate the interplay between contingencies and autocatalytic constraints in the emergence, persistence and eventually transformation of a socio-economic system. Second, we lay bare the concatenation of processes that distinguish the historical emergence of the capitalist dynamics

which underly the current anthropization process: the material conditions of production and reproduction, their impact on mental conceptions and institutions. Third, we recognize the growth-enhancing, centripetal tendency of autocatalytic configurations to increasingly direct resources towards itself. Within a capitalist configuration this tendency is expressed via the competitive search for maximum profit. In this respect we would like to point out how the pursuit of ever increasing economic affluence is incompatible with the planetary boundaries (Wiedmann et al., 2020). Fourth, we note how the autocatalytic configuration is not free from centrifugal tendencies or contradictions. In fact, these contradictions could be the seeds of an alternative configuration. Moreover, a corollary to the centripetal tendency of autocatalysis, is that its development is constrained by the available resources. The ultimate "contradiction" of capitalism, may indeed be its pressing against the earth biophysical limits (Harvey, 2014). Fifth, we expose the dialectical relationship between the material/economic sphere and the cultural/institutional sphere. For example, we discussed how in the emergence of capitalist agriculture in Salta the market became central to all the processes within the material/economic sphere (i.e., production, social relationship, reproduction) to emerge finally as the central institution also in the cultural/institutional sphere (i.e., access to land, logic of efficiency etc.). A successful transition beyond capitalism will also require the simultaneous action on both fronts: building up from the material/economic processes and reaching towards institutional/cultural ones. To conclude, our study helps to understand how capitalist dynamics, and its associated dangerous pattern of anthropization, emerge, expand, and develop within a specific historical context. The point, however, is to change them.

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SI.1 The Chaco Salteño and its early anthropization

The antiquity of the human occupation of the Chaco region in the pre-Columbian time remains uncertain. It is believed that hunter-gatherers populations settled in the region between 8,500-3,500 years before present (BP) as a result of favourable climatic changes[1,2]. Subsequently, around 2,000 years BP, new human groups migrated towards the Chaco from both the north and the south[3–5]. During the colonial period (16th-19th century), the region remained marginal. However, it is noteworthy the process of christianisation that began with the Jesuits (early 17th century) and, after their expulsion in 1767, continued under other religious orders. During this period the indigenous peoples also started to work seasonally on the sugar plants in the Chaco Salteño region. With the independence of Argentina from Spain (in 1816) the new Salta government promoted the advance of cattle rangers in the region. Following the establishment of what has been called "the neo-colonial order"[6], the military occupation and the settlement of squatters (from the indigenous point of view) in the region was actively pursued until the end of the 19th century. The increasing presence of livestock led to the rapid loss of natural pastures and started a process of soil degradation that lasts to this day. Another important economic activity, which occurred from the beginning of the 20th century, is the extraction of hard wood trees (mainly quebracho species). In the late 19th century, the establishment of new sugar plantations and sugar plants around Salta and Jujuy, relies on the (not always voluntary) work of indigenous peoples (manly from the Chaco ecoregion) who are seasonally employed, at least until the 1960s (when the harvest and processing of sugar cane becomes completely mechanized). The 1970s mark an important shift. On one hand the agricultural restructuring in the pampean region, implies a displacement of the livestock activities in the North-West of Argentina, including the Chaco Salteño region. On the other hand, large-scale intensive agriculture starts to penetrate the area, particularly with the production of beans[7]. This brief overview suggests that the region experienced successive phases of anthropization. However, until the end of the 20th century, the prevailing mode of land use and agricultural production was based on small-scale peasants' agriculture and hunting-gathering and fishing. That is to say, the Chaco Salteño remains relatively marginal in the context of capitalist agriculture. It is only from the second half of 1990s onwards, with the arrival of capital-intensive agriculture, that the situation changes dramatically, with important environmental and social consequences.

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