# THE SPIRALLING ECONOMY: CONNECTING MARXIAN THEORY AND ECOLOGICAL ECONOMICS

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## ABSTRACT

The capitalist mode of production and consumption is caught in a double bind: its expansion destabilises natural systems and fails to curb social inequities, while slowdown destabilises the inner workings of the economic system itself. To better understand what is happening in this phase of instability, this article proposes a System Dynamics representation that combines elements of Georgescu-Roegen's Ecological Economics with Marxian theory. It draws from another diagram recently developed by David Harvey to communicate Marx's political economy in its totality. Harvey's diagram is adapted to incorporate the flow-fund model developed by Georgescu-Roegen. The contribution is twofold. First, it visualises the connections between the two traditions. Second, it extends System Dynamics into (eco-)Marxian analysis.

## KEYWORDS

biophysical economics, ecological economics, system dynamics, Marx, Georgescu-Roegen

## 1. INTRODUCTION

Economic growth lies at the heart of a multidimensional crisis. While growth has been the norm over the past several decades, not everyone has received a fair share; already substantial income and wealth gaps continue to widen (Alvaredo et al. 2017). Even if this trend could be reversed with further economic growth, growth itself cannot be upheld indefinitely on ecological grounds. Economic growth over the past half a century was contingent on the increasing extraction of tremendous amounts of matter and energy from the environment, and outpouring of waste and

emissions from the economy (see Krausmann et al. 2009; Le Quéré et al. 2018). These increasing flows are destabilizing natural systems on a planetary scale (Steffen et al. 2015). Strongly coupled with ecological decline, the growth trajectory is bound to hit a wall (Meadows et al. 2005; Turner 2008). As ecological constraints prevent an indefinite growth of the economic pie, concerns about its unequal distribution within and between generations will become increasingly pressing (Rammelt & Boes 2013).

The crisis gives rise to a serious dilemma. In the current economy, when the mechanisms of growth fail, innovation stops, companies are outcompeted, recessions loom, banks collapse, businesses foreclose, people lose employment and governments default on their debts. Growth therefore continues to be the most important policy goal from left to right (Latouche 2009). The idea of growth also shapes societal aspirations and ideologies, such as personal achievement and upward mobility (Koch 2018). Many continue to hope against hope that economic growth will be decoupled from its ecological impact and will bring wealth to all. However, this merely obfuscates fundamental contradictions between the goals of economic profitability, environmental sustainability and social equity (Fletcher & Rammelt 2016).

We still only have a limited grasp of the dynamics and interactions of economic, environmental and social systems. Many are looking for answers in Karl Marx's descriptions of predominant socioeconomic structures under capitalism (Heinrich 2004; Brand 2016; Harvey 2017) and of their interactions with the natural world (Altvater 1993; O'Connor 1998; Burkett 2006; Magdoff & Foster 2011; Koch 2012).

This article proposes a system diagram that reveals the biophysical nature of market-capitalist economies. It builds on another diagram recently developed by David Harvey (2017: 1) in his effort "to systematise Marx's voluminous writings on political economy". Harvey's diagram is adapted and extended in line with several ecological readings of *Capital* (e.g., Burkett 2006; Magdoff & Foster 2011). Although not without contention, these interpretations overlap to some extent with the field of Ecological Economics (Georgescu-Roegen 1970; 1971; Gowdy & Mesner 1998; Daly & Farley 2011), which evolved to a large extent from Nicholas Georgescu-Roegen's *Bioeconomics*—a term that has been largely abandoned by ecological economists due to ambiguities with its usage (Giampietro 2019). Key concepts and relationships from Georgescu-Roegen's Ecological Economics and (eco-)Marxian theory are merged in the proposed representation. It is certainly not comprehensive. As an exercise in interdisciplinary integration, the representation is a rendition of a relatively small area of overlap between these extensive fields

of study.

The aim is to open a door into these interdisciplinary insights from a System Dynamics perspective (Forrester 1995; Meadows & Wright 2008). System Dynamics lends itself well for visualising the conceptualisations developed in Ecological Economics (Uehara et al. 2016); let us see what it can do for visualising key insights from Marx's *Capital*. His analysis has only received sporadic attention in System Dynamics (e.g., Goodwin 1967; Keen 2013; Saeed 2016; Rammelt 2018).

The article begins with a brief description of Marx's theoretical starting points and a synopsis of Harvey's diagram. This is followed by reflections on systems thinking and the challenges of representing complexity. The article then explores some commonalities and discrepancies between (eco-)Marxian and Ecological Economics perspectives. The methodological section includes descriptions of Georgescu-Roegen's 'flow-fund model' and of the System Dynamics modelling language (using the STELLA software platform). In the core section of the article, these tools are applied to adapt and expand Harvey's diagram. The new representation allows us to reflect on the forces that drive economic growth and its co-evolving social-ecological crisis. The article concludes with some reflections on the merits and limitations of the representation, and on possible ways forward.

## 2. Capital as value in motion

Marx was critical of generalisations of concepts such as labour, production or money across human history. These phenomena existed in different forms prior to capitalism and take on very specific forms under capitalism (Brand 2016). Drawing upon the philosophical traditions of dialectics and materialism, Marx attempts to grasp the contingent basis of abstract concepts prior to their application in the concrete world: "the method of rising from the abstract to the concrete" (Marx 1973: 101). He begins his narrative with the abstraction of capital as *value in motion* (Harvey 2017), which begs the questions: what is *value* and how does it move?

Marx defines wealth as anything useful, i.e., a *use-value*, created by human labour from the materials found in nature, such as a chair for resting, a bicycle for transportation or the tools to make these objects. The prevalent form of wealth in capitalist societies is the commodity: wealth produced with the intention to sell it on the market (as opposed to wealth produced for own use or consumption by its producer) (Heinrich 2004). Next to possessing a use-value, a commodity also has an *exchange-value*. In contemporary market economies, a commodity's exchange-value is

expressed by its price, e.g., paper bills or digital currency. If the exchange-value of a chair is equivalent to, say, 5% of the exchange-value of a bicycle, then the two must share some immaterial property that they possess to a lesser or greater degree: *value*. For Marx, the value of a commodity is determined by the average quantity of *labour-time*— or 'socially-necessary labour-time'— involved in its production. A bicycle is worth more than a chair because, on average, more labour went into producing it (Ibid.).

Labour-time is not only the source of value, but also of so-called *surplus-value*. To understand surplus-value, it is useful to note that labour-power (as opposed to the labourer) is also a commodity within capitalism. It has a use-value in production: its ability to create value. It has an exchange-value expressed by a wage. And, it has its own value: the average labour-time required to reproduce labour-power. This value is essential for understanding where profit comes from. Surplus-value is created by workers during the extra portion of labour-time above what it took to produce the value represented in their wages (Burkett 2006). In other words, surplus-value is the difference between the total value of production and the value consumed by workers.

The amount of surplus-value created by labour-power is increased by means of the use-values of machines (and processed natural resources, as discussed later). However, machines do not create value in Marx's conceptualisation; they only transfer their own value as they depreciate during the production process. Where does their value come from? It comes, of course, from the labour that went into producing those machines.

This brings us back to the definition of capital as value in motion. Capital is neither money nor commodity taken in isolation, but rather the ceaseless cycle of appreciation of value, i.e., "self-realising value" (Marx 1973: 746). Initial money is invested (M) to produce commodities (C) "whose value exceeds that of their component parts, and therefore contains the capital originally advanced plus a surplus-value [M']" (Marx 1976: 709). Surplus-value partly returns to the producer to fuel the production of more commodities, more surplus-value, and so on. This represents Marx's basic cycle of exchange (M–C–M')—economic growth in its most elemental form.

Marx's opus does not start with an overall map of capital, but sets out to gradually uncover this map through a step-by-step examination of the process. He often mentioned his ambition to depict capital as a totality, but was unable to do so in his lifetime (Harvey 2017). In Figure 1, the depiction proposed by Harvey shows how capital cycles through the phases of production, realisation and distribution. "This cycle, in which the same phases are continually gone through in

succession, forms the circulation of capital" (Marx 1976: 709).

Insert here: Figure 1 - Harvey's representation of Marx's Capital (Adapted from Harvey 2017: 6, Figure 2, "The paths of value in motion as derived from the study of Marx's writings on political economy.")

Initially, money capital is spent on purchasing means of production and labour-power. As indicated in Figure 1, the produced commodities are classified by Marx as wage goods (consumer goods for workers), luxuries (consumer goods for the bourgeoisie) and new means of production (productive goods for capitalists). For buying and selling to occur on the market there has to be demand originating from our wants, needs and desires. To be effective, demand must also be backed by sufficient purchasing power. The selling of commodities eventually realises more money than what was originally invested as money capital (through the creation of surplus-value). This money is then distributed to different claimants, e.g., as wages to labour, profits to capitalists, taxes to government, interest to bankers and rents to landholders. This is where the cycles are 'closed': the capitalist reinvests profits in production, the labourer spends wages to purchase wage goods, and interest payments flow to the banking system where new money capital is created (Harvey 2017).

In his introduction, Harvey likens capital to water in the hydrological cycle, which "depicts $H_2O$ passing through different forms and states at different rates before returning to the oceans to start all over again. This is very similar to how capital moves" (Harvey 2017: 3). $H_2O$ molecules are the common substance in the hydrological cycle; value is the common substance in the economic cycle. The analogy immediately comes with a caveat: "the volume of capital in motion is constantly expanding at a compound rate" (Harvey 2017: 3). In Marx's own words: "By describing its circle it [capital] expands itself as the subject of the circle and thus describes a self-expanding circle, a spiral" (Marx 1973: 746).

## 3. A systems perspective on capital

The spiralling economy is driven by a self-expanding cycle or, in the language of systems, a reinforcing feedback loop. This is a pathway of causes and effects that circles back upon itself to boost the original cause (Meadows & Wright 2008).

Such connections between systems thinking and Marxian thought are not new (see Levins & Lewontin 1985; Altvater 1993; Levins 1998; O'Connor 1998). Dialectical materialism and today's

systems science both grapple with the contradictory forces that arise from patterns of relationships within a system. However, systemic and dialectical approaches proceed to study processes of change over time in distinctive ways. While systems science generally relies on mathematically expressed relationships and model simulations, dialectical analysis is to a large degree qualitative (while also dealing with quantitative dimensions). This is an interesting point of contention, but beyond the scope of this paper (see Forrester 1995; Levins 1998). System Dynamics will only be applied as a drawing tool, not as a simulation tool.

*Capital* begins with a fundamental element: the commodity. Each volume then deals with a different part of the cyclical process—a different sub-system so to speak. Only when all three volumes are combined does Marx's "organic system" appear as a totality of many elements and relations (Marx 1973: 278). Any attempt to capture this totality in a single diagram will have to leave out a great deal of its component parts. Systems thinking recognises that scaling up to the aggregate system inevitably implies that particular details should be ignored (Levin 1992). Otherwise, the model—as a tool for understanding—would become increasingly self-defeating. A good representation of the system is therefore a deliberate caricature that attempts to capture and communicate only certain features of interest (Meadows & Wright 2008).

The questions then become: which components do we include or omit, and how much simplification do we get away with? The answers depend upon the object of study. Harvey aimed to represent "a simplified … map of capital flows" (Harvey 2017: 44). This is a different map from one that would emphasise biophysical processes. For example, "[w]hen commodities that are the bearers of value are finally consumed they drop out of circulation … But this disappearance is contingent on the prior conversion of value from the commodity into the money form, and money has the capacity to remain in circulation in perpetuity" (Harvey 2017: 172). In other words, while value circulates indefinitely, material components 'disappear' in Harvey's diagram. His analogy with the hydrological cycle is suitable in the case of value in motion, but limited from a biophysical perspective. Matter and energy do not circulate in the economy like $H_2O$ in the hydrosphere: matter and energy enter and exit the economic system at many different points.

Moreover, value and matter also typically take opposite directions. "[A]n increased quantity of material wealth may correspond to a simultaneous fall in the magnitude of its value" (Marx 1976: 136-137). This happens, for example, when an increase in the productivity of labour produces more wealth with less labour-time. Since labour-time is the source of value, total value falls while the total amount of material wealth grows (Harvey 2011).

With an emphasis on value, Harvey's diagram intentionally omits and simplifies Marx's biophysical considerations. Machinery, materials, work, goods, services and currencies embody, create or represent value in some form or another, but they are also entities with fundamentally diverse material and energetic characteristics. Matter and energy will undergo different movements, accumulations and qualitative transformations in the economic processes of production, maintenance, utilisation, transportation, consumption and reproduction. These are the biophysical dimensions that the proposed representation aims to highlight.

## 4. A biophysical perspective on capital

Seeing the economy as a biophysical phenomenon represents an area of common ground and disciplinary tensions between Marxian theory and Ecological Economics.

First, both traditions perceive the economy as an open system that exchanges matter and energy with its surroundings (Maneschi 2006). (In contrast, the hydrosphere is a materially-closed system.) The economy relies on the extraction of matter-energy from original natural resources all the way to final waste and emission (Giampietro 2019). Ignoring this "is analogous to a biologist describing an animal only in terms of its circulatory system, without ever mentioning its digestive tract" (Daly & Farley 2011: 29). This metabolic flow, or so-called *throughput*, is a well-known central tenet in Ecological Economics (Ibid.).

Few recognise that the ecological notion of metabolism was initially extended into the domain of political economy by Marx (Burkett & Foster 2006). "The labour process … is an appropriation of what exists in nature for the requirements of man. It is the universal condition for the metabolic interaction [Stoffwechsel] between man and nature" (Marx 1976: 290). In Marx's metabolic analysis, "[c]apital as a system was intrinsically geared to the maximum possible accumulation and throughput of matter and energy, regardless of human needs or natural limits" (Foster 2015: 7).

Second, Marxian theory and Ecological Economics both reflect on the thermodynamic nature of this throughput (Burkett & Foster 2006; Koch 2012). Thermodynamics is a branch of physical sciences concerned with how energy changes from one form to another (Mayumi 2017; Giampietro 2019). The first law of thermodynamics states that energy can neither be created, nor destroyed; it can only change form. The second law tells us that entropy—simply put, a measure of energy dissipation—increases as matter is transformed in the economic process. In other words, "[a]n entropic flow is simply a flow in which matter and energy become less useful; for example,

an animal eats food and secretes waste and cannot ingest its own waste products. The same is true for economies" (Daly & Farley 2011: 29). Climate change is a prime example. The burning of fossil fuels since the industrial revolution has been accompanied with an inevitable rise in entropy through heat and carbon dioxide emissions (Koch 2012). Even though the science had only started to emerge in Marx's time, "[t]hermodynamics is to be found in the very pores of [his] analysis" (Foster & Burkett 2008: 25). This will be illustrated in more detail later.

Third, Marxian theory and Ecological Economics both distinguish between the material and the monetary worlds. For Marx, this distinction follows from the difference between use-value and exchange-value (Burkett 2006; Magdoff & Foster 2011). Use-values are directly related to biophysical transformations when commodities are produced or consumed. These considerations are side-lined in the neo-classical understanding of commodities as mere monetary exchange-values (Koch 2012). Marx made no presumption that exchange-values accurately correspond to use-value or even to value, i.e., embodied labour-time (Jalee 1977; Heinrich 2004). Ecological economists define value differently as we shall see, but they also distinguish between wealth and money. They refer to wealth as biological and physical entities—land, raw materials, commodities, infrastructure, livestock, and so on. In contrast, money is a medium of exchange counted in dollars and cents. When it is stored, money is also a recognised claim to future wealth (Soddy 1933). Unlike wealth, however, money does not obey the laws of thermodynamics. Unlike energy, credit money can be created and destroyed. The record of an amount of digital currency does not decay over time—unlike the computer system on which it is recorded. Inflation may reduce its purchasing power, but this is not determined by a physical law of nature (Daly & Farley 2011).

While they share common ground, Marxian theory and Ecological Economics are also divided on several issues, most notably on the incorporation of natural resources in a theory of value.

Marx (1976: 751) referred to natural resources as "something provided by nature free of charge". He was reflecting on the tendency in capitalism to treat the natural conditions of production (underground minerals, fertility of the soil and so on) as free gifts. For example, crude oil is the 'free gift' of ancient sunlight and photosynthesis; it was not created by capital. At the initial stage, a mining company simply pays rent to get access to the resource. Later, as crude oil is extracted and refined into gasoline, value is added by human labour-power (Foster & Burkett 2018). During production, some of the value embodied in the equipment of the refinery is transferred to the gasoline. Gasoline is then sold and consumed in other processes, e.g., in the production of cars. In this case, gasoline becomes a use-value in a new production process. As it is consumed, the value

of the gasoline is transferred to the value of the cars. Gasoline and other processed natural resources therefore "acquire (but do not create) value" under capitalism (Ibid.: 16). Similarly, trees produce wood (use values), but the wood only acquires value with the labour-power that goes into producing timber. In other words, from the Marxian perspective, nature represents *potential value* until human labour has come in to give it *value* (Jalee 1977).

Marxian theory conceptualises value within the specific conditions of market-capitalism. In contrast, several currents in Ecological Economics reflect on the meaning of value beyond those conditions with the aim to improve environmental decision-making (O'Neill & Spash 2000). These proposals build on the idea of value pluralism (O'Neill 2017). For example, Douai (2009) presents a typology of environmental use-values beyond the economic realm (e.g., recreational, historical, symbolic or life-supporting) which rely on alternative non-market modes of valuation (e.g., benevolence, tradition, ethics or aesthetics). Such conceptualisations reveal a range of values that are systematically being encroached on by the commodification of nature under capitalism.

While some ecological economists take the view that nature *consists of* (use) values, others assert that it *creates* value (Martinez-Alier 1987). For example, Kallis (2018: 51) argues that "[w]hat is common, physically speaking, in two commodities that exchange is not just salaried labour. They embody energy, matter and unpaid labour too... For capital, these are equally *important sources of surplus and value* in exchange: the more of them there is, the less salaried labour time is needed" (2018: 51, emphasis added). Marx was sceptical of similar perspectives advanced by the Physiocrats who, in his opinion, conflated nature's contributions in the form of use-values with value creation by human labour. They were consequently unable to clearly discern the source of surplus-value in labour exploitation, and to distinguish this exploitation from the appropriation of nature's 'free' use-values (under capitalism). Some strands of Ecological Economics are accused of similar oversights (see critique in Burkett 2003; 2006; Foster & Burkett 2018).

In the specific Ecological Economics of Georgescu-Roegen, natural resources form the basis—along with human effort—for the production of material wealth. Economic value is not ascribed to nature directly, nor to one factor of production in particular (Gowdy & Mesner 1998). Rather, value is generally ascribed to low entropy ordered structures. "[E]very object of economic value—be it a fruit just picked from a tree, or a piece of clothing, or furniture, etc.—has a highly ordered structure, hence, a low entropy" (Georgescu-Roegen 1993: 80). However, Georgescu-Roegen adds, "this is only the material side of the process. The true product of the economic process is an immaterial flux, the enjoyment of life" (Georgescu-Roegen 1976: xiv). In Marxian terms, such a

definition of value could be referred to as an "immaterial use-value" (Burkett 2003: 140)—one that cannot be measured in hectares, tons or joules. While it is immaterial, this flux nevertheless feeds on "the entropic transformation of *valuable* natural resources (low entropy) into *valueless* waste (high entropy)" (Georgescu-Roegen 1976: xiv, emphasis added).

On one level, Georgescu-Roegen and Marx both theorise that nature is instrumental in the production of wealth. On a deeper level, they formulate quite distinct conceptualisations of value based on different intellectual concerns and approaches. Georgescu-Roegen derives his interpretation of value from biophysical and thermodynamic foundations. Marx, on the other hand, starts with the abstract world of value before applying it to the concrete world. Can these views be reconciled? From the above, an interpretation of Harvey's diagram in line with Georgescu-Roegen's Ecological Economics seems, at least partly, consistent with Marx's understanding of metabolic and entropic processes. The discrepancies that arise from an attempt to bridge the two approaches relate mostly to the different conceptualisations of value. The discussion section will return to this question. For now, let us focus on the biophysical dimension.

## 5. The flow-fund model and system dynamics

The diagram presented in the next section relies on concepts from Ecological Economics and on the modelling tools of System Dynamics. A key distinction in both Ecological Economics and System Dynamics is between so-called *stocks* and *flows* (Meadows & Wright 2008; Daly & Farley 2011). Stocks can be regarded as accumulated quantities of consumable material, such as apples, water or coal. Flows are the processes whereby stocks increase (inflows) or decrease (outflows). An inflow could be picking apples; an outflow would be eating the apples or letting them spoil. The inflow extracts low entropy matter and energy from the natural environment. The outflow ultimately returns high entropy matter and energy to the environment. An example of such a process is represented in Figure 2. The clouds in Figure 2 indicate the boundaries of our representation. More specifically, they symbolise either the source of fish, or the outlet (i.e., sink) for waste after the fish have been consumed.

Insert here: Figure 2. Example of stocks, flows, funds and fluxes

The other key element in the diagram is the causal link (Meadows & Wright 2008). The 'o' on the link in Figure 2 indicates the cause 'opposes' the effect. In other words, if the former rises or expands, the latter falls or shrinks. For example, when the fisher runs out of fish; he/she can be assumed to want to catch again and refill his/her store. A decreasing stock leads to an increasing

inflow (the effect goes in the 'opposite' direction). This particular causal chain creates a 'balancing' feedback loop: it opposes or self-corrects the original change (Ibid.). As the store of fish is being refilled, the production inflow gradually drops. As we shall see, an 's' link indicates a change in the 'same' direction.

Ecological Economics adds a further distinction between a stock of wealth that is consumed and a *fund* of wealth that is utilised (Georgescu-Roegen 1971). Funds include non-perishable assets, such as houses, ploughs, shipyards or boats. Funds arise from inflows of production and maintenance. They also have an outflow of deterioration as they undergo wear and tear. Funds, as opposed to stocks, "are not consumed in the process; instead they come out of the process, albeit with some scars" (Ibid.: 225). *Fluxes* are different from flows: they represent the processes of using, rather than consuming, funds. Fluxes thus do not directly drain the funds, but contribute to their wear and tear. This process is represented in Figure 2 by the grey fund and flux variables. The 's' links indicate that more fishing boats imply more potential utilisation, which implies more depreciation and fewer boats. This represents another balancing loop. Causal links can also be arranged in a reinforcing loop, e.g., when investment in commercial fishing leads to more selling of fish, which leads to more profit and investment (M-C-M').

Several flows originate from, or end up in, the natural environment. Primary energy sources are required to produce stocks and funds, and to maintain the latter. During production and maintenance, some of this energy accumulates in the stocks and funds, and the rest is used up—that is, it is dissipated as waste heat. The energy accumulated in the stocks and funds eventually also dissipates when food, fertiliser and fuel are consumed, or when oxen, tractors and other tools wear out, corrode and decay. As resources are thus inevitably transformed into waste, the overall entropy increases (Georgescu-Roegen 1971). To counteract this inexorable material loss and to sustain consumption flows and utilisation fluxes, people must contribute efforts and natural resources towards the inflows of production and maintenance.

Figure 2 contains only biophysical variables. Monetary variables should of course not be ignored as they are affecting and affected by the biophysical variables. For instance, an outflow from a stock of fish might be sold to generate an income; a maintenance inflow into a fund, such as a boat, might require financial expenses; the same boat might provide the collateral for securing a loan. Essentially, financial variables are linked to, rather than used as measures or representations of, biophysical variables. Both will be incorporated in the proposed diagram of *Capital*.

Why emphasise all these distinctions? Stocks and flows reveal and hide different pieces of

information. For example, the weekly amounts of commodities transported to the market and purchased by consumers (flows), do not tell us much about the sizes of wholesaler inventories or household reserves at a particular point in time (stocks). Another problem arises if we ignore flows and focus exclusively on stocks: if the magnitude of an inventory (stock) is identical at the start and end of the year, it is impossible to tell whether it remained constant or whether it was evenly drained and refilled (flows) (Georgescu-Roegen 1971). To borrow Harvey's analogy, a representation of the hydrological cycle would be seriously incomplete if it only depicted flows (evaporation, transpiration, condensation, precipitation and infiltration) and left out the stocks (oceans, ice caps, glaciers, aquifers, lakes and rivers).

An explicit distinction between stocks and funds is also necessary. A boat could be perceived as a material stock of wood, nails and other components. However, the term *stock* means something different when we talk of a stock of fish. "[A] more discriminating (and hence safer) way of describing a machine is to say that it is a fund of services" (Georgescu-Roegen 1971: 226). Finally, it is better to avoid referring to a 'flow of services'. Instead, we can refer to it as a flux. "Like any flow, the flux of life enjoyment has an intensity at each instant of time. But in contrast with a material flow, it cannot accumulate in a stock" (Ibid.: 284).

Despite these distinctions, Georgescu-Roegen understood that stock, flow, fund and flux concepts are dialectical. For example, a glacier seems like it is a stock, while in reality, it is a very gradual flow. "[A] flow is a stock spread out over time" (Georgescu-Roegen 1971: 223). However, no dialectical concept overlaps with its opposite all the way. "Though they are not discretely distinct, dialectical concepts are nevertheless distinct" (Ibid.: 47). For an analysis of glacier dynamics, it is useful to perceive them as stocks that are replenished by an inflow of snow at the top and drained by an outflow of meltwater at the bottom.

Georgescu-Roegen's framework described here is known as the 'flow-fund model' in reference to the two fundamental elements involved in production (Giampietro 2019): "in a reproducible process, the fund elements are the immutable agents that transform some input flows into output flows" (Georgescu-Roegen 1970: 4). How compatible is this model with Marx's *Capital*? The process of constructing the diagram in the following section will shed light on this question, and we will return to it in the conclusions.

## 6. Capital as a flow-fund system

This section presents a step by step construction of the diagram. The dark-coloured stocks and

flows represent financial variables (see Figure 3). This sets them apart from the biophysical world of stocks, flows, funds and fluxes. The funds and fluxes are light grey, so as to distinguish them from the stocks and flows.

Insert here: Figure 3. Key to the diagrams

In Figure 4, the capitalist starts with *money capital*. It is likely to initially enter the system in the form of a bank loan, i.e., a flow of *producer borrowing*. Money capital could also be acquired from loan-sharks or shareholders, but their money would already have been in the system. Most of the money currently in circulation originates from the commercial banking sector (Keen 2013). With it, the capitalist invests in the means of production, i.e., *productive goods*, referred to by Marx as 'constant capital'. A biophysical flow of *buying productive goods* is paid for by a monetary flow of *producer spending* in Figure 4 (consumer goods and spending will be incorporated later).

Insert here: Figure 4. Partial model: money capital, productive goods and the production of more productive goods.

The *purchased productive goods* (or 'constant capital') include *productive stocks* and *productive funds*. The *productive stocks* represent Marx's 'circulating capital' or 'materials of production'. These include raw materials, supplies, energy and other goods that are consumed during production. The *productive funds* represent Marx's 'fixed capital' or 'instruments of production', such as buildings, machinery, tools or other equipment that is utilised during production. Together, the stocks and funds generate a flow of *producing new goods*. First, the production of, say, automobiles relies on the consumption of stocks, such as plastic, glass and steel (*consumption of productive stocks*). Second, production relies on the utilisation of funds, such as buildings, machinery and tools (a flux of *use of productive funds*). Marx (1976: 753) also noted the distinction: "instruments of labour such as machinery, etc. … are not consumed, and therefore not reproduced or replaced, until long periods of time have elapsed". It is also possible that *producer spending* goes towards purchasing services from other capitalists, such as leasing transportation or renting real estate. In that case, the capitalist buys only the flux, not the fund—as indicated by the link between a duplicate variable of the *producer spending* flow and the flux of *use of productive funds* in Figure 4.

The utilisation of machines leads to their wear and tear. This is captured by the outflow of *depreciation of productive funds* in Figure 4. The 's' link from *use of productive funds* (flux) to *depreciation of productive funds* (flow) indicates that the more intensively those machines are

utilised, the faster they depreciate (i.e., a causality in the 'same' direction). The 's' link from *productive funds* to their depreciation simply indicates that more machines imply more depreciation.

Marx recognized the importance of friction and other forces of wear and tear, consistent with the entropy law. He even distinguished between the physical deterioration of machinery arising from use and the deterioration arising from lack of use. "Deterioration of the first kind is more or less directly proportional, and that of the second kind to a certain extent inversely proportional, to the use of the machine" (Marx 1976: 528). Strictly speaking, the aforementioned 's' link from the use flux to the depreciation flow in Figure 4 should therefore change into an 'o' link (i.e., a causality in the 'opposite' direction) whenever the magnitude of the use flux becomes too low.

While *productive funds* are utilised and depreciate ('fixed capital' in Marx), *productive stocks* are consumed and degrade ('circulating capital' in Marx). In Marx's terms, some means of production "become worn out through use" while others "are partly (e.g. in combustion) dissolved into their elements again" (Marx 1973: 90). In Figure 4, the *consumption of productive stocks* is a direct outflow from the *productive stocks*. For example, an inventory of steel plates in a car manufacturing company is emptied during the production of cars. The outflow of *degradation of productive stocks* corresponds to the corrosion of the steel plates held in inventory. With a falling inventory of steel plates, new ones will be purchased from a steel mill to bring the inventory back to a desired level. The added 'o' link in Figure 4 therefore indicates that whenever the stores of *purchased productive goods* fall, the inflow of *buying productive goods* rises.

Not all matter and energy in the flow of *consumption of productive stocks* is transferred to the flow of *producing new goods*. Some is released as waste and emissions (in the cloud at the end of the flow of *consumption of productive stocks*). Recycling of this waste is accounted for in the following way: if scrap metal from one production process is perceived as valuable for another process, it becomes a good that will be sold in the same way as metal sheets are sold by a steel milling company to a car manufacturing company.

Production also relies on inputs of *natural resources*. For example, the steel plates that are consumed during the manufacturing of cars must first be produced from iron ore in steel mills. Figure 5 therefore incorporates virgin *non-renewable stocks* (e.g., iron ore) that are consumed in the production of *productive goods* (e.g., steel plates). The outflow of *consumption of non-renewable stocks* drains the stock. Naturally occurring oil, coal, gas, iron, aluminium, copper, uranium and other minerals are all *non-renewable stocks* of (finite) *natural resources*; they do not

regenerate (at least not in a relevant timeframe). On the other hand, *living renewable stocks*, such as trees, fish or plants, reproduce through the flow of *regeneration of living renewable stocks* added in Figure 5. Not all the matter and energy contained in the consumption flows of (non-)renewable resources is transferred into the flow of *producing new goods*; there are residual losses.

Insert here: Figure 5. Partial model: incorporating natural resources.

*Natural resources* also include land, which represents a fund when it is considered as pure Ricardian land (Georgescu-Roegen 1971). The *use of land* is a flux paid for as rent to the holder of the land—hence the causal link from *producer spending* in Figure 5. To extract iron ore, the mining company pays rent to the property owner for the right to excavate the minerals buried underneath the property. The 's' link from *use of land* to *consumption of non-renewable stocks* indicates that the more mineral rights one controls, the more *natural resources* can be extracted. Beyond Ricardian land, however, industrial agriculture depletes soils of nutrients, microorganisms and other *natural resources*. In Figure 5, soil life depletion is included in the flow of *consumption of living renewable stocks*, which drains a *living renewable stock*. Finally, non-living renewables, such as wind, sun and gravity, do not drain any stock. They are represented as separate *non-living renewable flows*.

The diagram omits several complex social-ecological interactions. Environmental flows in managed ecosystems are constantly being modified in order to increase economic productivity (Giampietro 2019). This happens for instance when the natural deposition of nitrogen in soils is supplemented with the application of artificial fertilizer in order to boost biofuel crop yields. This does not mean that limits to growth have been overcome: other limits such as fossil fuel depletion or soil erosion will be exacerbated. The diagram omits these human impacts on natural flow-fund systems (Ibid.).

Production relies not only on *purchased productive goods* and *natural resources*, but also on labour. The capitalist does not acquire the *working population*, but its *labour-power* for a fixed period of time in return for *wages*. Marx viewed the *working population* as a fund, but then equated *labour-power* with a flow that drains the workers of their energy (Georgescu-Roegen 1971). According to Georgescu-Roegen, the *working population* is indeed a fund, but contrary to Marx, *labour-power* is therefore not a flow but a flux. It is incorporated as such in Figure 5 (see further reflections on this discrepancy in the discussion). Either way, in Marx's *Capital*, *labour-power* creates value and surplus-value, both of which are embodied in the flow of *producing new goods*. For example, the processing of iron ore into metal sheets involves the addition of value by *labour-power* in a steel

mill. As labour only gets paid *wages* for the labour-time it took to produce value, surplus-value can be claimed to fuel growth in the spiralling economy. Marx referred to labour-power as 'variable capital' because it creates new value during production, as opposed to 'constant capital' (*productive goods*), which only transfers some or all of its value).

Insert figure: Figure 6. Partial model: incorporating labour-power and the distribution of revenue.

The magnitude of the flux of *labour-power* employed in the flow of *producing new goods* depends on the productivity of labour, i.e., the amount of goods that a worker produces in a given amount of time. Labour-saving innovations reduce the *labour-power* relative to the *use of productive funds* at a given level of production, which gives rise to surplus-value and potential profit and investment. Marx discussed at length the repercussions of this process on employment, prices and investment. Marx also reflected on how rising labour productivity affects the system's metabolism. "[T]he increasing productivity of labour is expressed … in the increasing mass of raw material that is transformed into products, worked up into commodities, in one hour, for example" (Marx 1981: 203). In his view, capitalism's unprecedented advances in labour productivity therefore translates directly into tremendous increases in the throughput of matter and energy (Foster & Burkett 2008).

The presumed motivation for investment under capitalism is the expectation that, at the point of realisation, the selling of goods will generate more than their production costs (Harvey 2017). Steel mills will generally expect a profit from selling their product to car manufacturers. As the diagram depicts the entire productive sector, a flow of buying is simultaneously a flow of selling, which is added to the *total revenue* stock. The same goes for the buying and selling of services, such as leased buildings, trucks or other equipment. Figure 5 distinguishes these payments for the *use of productive funds* from the rents paid for the *use of land*, which represents a natural resource, not a man-made productive good.

The *total revenue* is then distributed between different claimants, including *wages* to workers for their *labour-power*, *interest* to bankers (on debt created by the flow of *producer borrowing*), taxes to the government (not included in the diagram) and *profits* to capitalists. This 'closes' a key reinforcing feedback loop: productive goods (e.g. steel plates) are purchased by the capitalist to produce other productive goods (e.g. trucks), which are then sold to other capitalists. *Profits* can potentially flow back through *producer spending* to purchase more productive goods (e.g. assembly automation). This feedback loop explains exponential growth of the cycle of exchange (M-C-M'). (Alternatively, *profits* can be invested in financial markets, but this has not been

incorporated in the diagram.)

So far, the focus has been on capitalists that produce, sell, buy and utilise productive goods and services. Figure 7 incorporates consumer goods and services. The added structure in the left part of the diagram mirrors to some extend the structure on the right.

Insert here: Figure 7. Total model: incorporating consumer goods and services, and labour reproduction.

For Marx, capitalism relies on a large proportion of the population not having access to the means of production. This group relies on waged-employment to buy the commodities supplied by capitalists (Harvey 2017). In Figure 7, the *working population* sells its *labour-power* to earn *wages* that accumulate in a stock of *savings*—however briefly. Their *savings* are spent through an outflow of *consumer spending*, which causes a flow of *buying consumer goods*, such as the purchase of a new private car (and a rise in *total revenue*). If, on the other hand, *consumer spending* goes towards purchasing services, e.g., a taxi ride, the outflow of *consumer spending* causes a flux of *use of productive funds*.

This flux is sold to consumers by the taxi company that owns the cabs (*productive funds*). The taxi driver is part of the *working population* and sells his or her *labour-power* for a wage to the taxi company. This interpretation differs from the Marxian view that a taxi ride is simultaneously an act of production and consumption. (The discrepancy is picked up again in the discussion.) A self-employed taxi-driver could be perceived as being both capitalist and labourer (or neither); he can be seen as earning profits and wages simultaneously. A self-employed Uber driver will purchase online services from the Uber company (a flux of use of Uber's computer system). While such types of arrangements are increasingly common, it goes beyond the scope of this paper to further unpack them.

Earlier, Figure 4 distinguished between the stocks that are consumed and funds that are utilised by producers. Similarly, *purchased consumer goods* in Figure 7 include *consumer stocks*, such as food, detergent, fuel and other non-durables which are drained by the flow of *consumption of consumer stocks*. Consumer goods also include *consumer funds*, such as cutlery, clothes, furniture, electronics and other so-called 'durables' that provide a flux of *use of consumer funds*.

As with productive goods, consumer goods also deteriorate. A dishwasher that is intensively used will depreciate faster and will need to be replaced more frequently. Tomatoes, on the hand, degrade until they decompose. The causal link from *purchased consumer goods* to the flow of

*buying consumer goods* in Figure 7 indicates that the faster a household empties its stores, the greater the inflow of new purchases. The frequency of consumption varies between stocks and funds. As Marx (1976: 276) noted, "[s]ome of the means of subsistence, such as food and fuel, are consumed every day, and must therefore be replaced every day. Others, such as clothes and furniture, last for longer periods and need to be replaced only at longer intervals".

Finally, Figure 7 incorporates the process of *labour reproduction*. The labourer maintains his or her ability to work, i.e., reproduces his or her own *labour-power* through the everyday activities of cooking, washing, resting, and so on. The flow of *labour reproduction* relies on the consumption of stocks and the use of funds at a given standard of living. It also relies on so-called 'free gifts of human nature', i.e., the knowledge, work ethic and skills of labour. Much of these 'free gifts' are provided by households (usually women) with some assistance from the state (Harvey 2017). Here too, the diagram is highly simplified; it glosses over many of the complexities involved in social reproduction. Another essential feedback loop is closed here. The working population works and spends its wages on consumer goods and services to support its own reproduction. Labour reproduction 'regenerates' labour-power for the production of new goods and services.

## 7. Discussion

The representation reveals significant overlap between Marxian theory and Ecological Economics. Both perspectives recognise the economy as an open system, the entropic nature of throughput (metabolism), the distinction between fund and stock elements (fixed versus circulating capital), and the distinction between money and wealth (exchange-value and use-value).

The process of building the diagram also brought up several discrepancies. For example, a taxi ride represents a commodity to be sold on the market. From a Marxian perspective, "the act of production is concurrent with the act of consumption (as the taxi driver produces a change of place, I consume it)" (Heinrich 2004: 44). Ecological Economics deconstructs and categorises the process differently. Production is associated with the creation of material wealth, i.e., the vehicle itself. Consumption is associated with a material flow that drains a stock, e.g., petrol from the taxi's fuel tank. What is sold to the customer is the taxi ride, which represents a use flux derived from a fund element (the vehicle), not a flow of production or consumption.

The difference may seem trivial, but it is part of a broader Ecological Economics critique of Marxian theory for confusing flows with fluxes. Here is another example: Georgescu-Roegen approvingly writes: "It is beyond question that Marx started by viewing the worker as a

fund" (Georgescu-Roegen 1971: 233). The error, according to Georgescu-Roegen, lies in Marx's omission of the service flux associated with this particular fund (Maneschi 2006). Marx associates labour-power with the expenditure of "a definite quantity of human muscle, nerve, brain, etc" (Marx 1976: 274-275). Elsewhere Marx states that "[t]he purchaser of labour-power *consumes* it by setting the seller of it to work" (Ibid.: 283, emphasis added). According to Georgescu-Roegen, by equating labour-power to a flow of consumption of energy, Marx reduces the worker to "a mere stock of energy" (Georgescu-Roegen 1971: 234). However, the worker must be present with the aggregate of his or her mental and physical capabilities. Therefore, "[a] service must not be confused with a partial decumulation of one's stock of energy even if one insists on considering only the material factors of an economic process" (Ibid.). If the worker is a fund, its labour-power must be a flux. Georgescu-Roegen gives the following explanation for the error: "So eager was Marx to avoid the slightest suggestion of the idea that the services of capital proper may contribute to the value of the product something more than the value of the maintenance flow, that he painstakingly avoided any reference to services even in the case of the labourer" (Ibid.: 233).

The flow-fund distinction is then a key aspect in the enduring debate between (eco-)Marxist thinkers and ecological economists on the source of (surplus) value. The present discussion will simplify and highlight only a few threads from these elaborate arguments (for further details, see Kallis & Swyngedouw 2018; Foster & Burkett 2018).

In Marx's *Capital*, human labour alone creates *(surplus) value*. Natural resources do not create *value*, but provide *use-values* to production. When these resources are processed with the application of labour-power (e.g., crude oil into gasoline, or trees into timber), they acquire value. This embodied-value can later be transferred to the output of other production processes (e.g., bicycles or chairs). By saying that nature and labour both create value, we lose track of the difference between the exploitation of workers and the appropriation of nature. This would muddle Marx's contribution to understanding the capital-labour conflict. On the other hand, some ecological economists worry that Marx's framework misses the tremendous amount of work done by nature by accounting for it only indirectly through rent and increased productivity. To this, some Marxist theorists respond that Marx was looking at how capitalism frames value, not at how value *ought to be* framed. It seems that this is where the debate stalls.

The conceptualisations of value reflect distinct concerns regarding the economic process, such as the exploitation of labour, the depletion of resources, the entropic character of production or some

combination of the above. The disciplines have their own priorities and do not need to fold into each other all the way. However, their overlap has clearly led to interdisciplinary tensions. To move forward, it is important to expose the assumptions underlying the concept of *value*. In such a dialogue, nature's contribution to capitalist production could perhaps be referred to as the creation of *(potential or natural) use-values*, rather than *values*. The value created by labour-power could be specified as *commodity-value*, *embodied-value* or any other appropriate designation. One could then refer to *a transfer of embodied-value* from processed natural resources, rather than the *creation of new value by* those resources. Of course, these are just language conventions, but they are essential to a constructive debate.

## 8. Conclusions

This paper's inspiration came from David Harvey's representation of capital as value in motion. Marx ultimately applies this concept to the concrete world, which is both connected to and distinct from the realm of value (value self-expands indefinitely within the system, while matter-energy typically takes opposite directions within the system, and flows in and out of it). The aim of this article was to focus on Marx's biophysical considerations through the lenses of Georgescu-Roegen's flow-fund model.

The diagrams reveal a multitude of biophysical connections between the economic system and its encompassing natural system. These include high-entropy outflows of matter and energy from consumption, degradation or deprecation, as well as low-entropy flows of regeneration and consumption of natural resources. The diagrams also help to distinguish between different forms of inequality, such as: uneven distribution of revenue; unequal access to material flows and immaterial fluxes through exchange; gaps in the monetary stocks of money capital and savings; asymmetric ownership of material stocks and funds; uneven control over production flows; or unequal exposure to waste flows. Finally, they depict several key feedback loops that drive the spiralling economy: production engenders profits, investment and further production; labour-power results in wages, consumption and in further reproduction labour-power.

Like all models, the diagrams are also limited in what they reveal. Several simplifications were already mentioned, such as the precise functioning of the credit system, the role of financial markets, the precise contributions of the free gifts of human nature to labour reproduction, and the human impacts on natural flow-fund systems. These simplifications present opportunities to expand the diagrams in many directions.

The obvious overlap between the disciplines also leads to tensions in the biophysical dimension of the subject matter (e.g., labour-power as a service flux versus an energy flow) and in its value dimension. Attending to these tensions is important if we are to better understand the fundamental contradictions that arise from the spiralling expansion of exchange-values, the unsustainable appropriation of nature's use-values and the unequal control over surplus-values. The proposed diagram hopefully contributes to the wider efforts of improving that dialogue. For that purpose, the Ecological Economics flow-fund model has much to offer. With it, "Marx's tour de force lets itself be seen in detail and admired" (Georgescu-Roegen 1971: 233).

## 9. References


Altvater, E. 1993. *The future of the market*. London: Verso.

Alvaredo, F., L. Chancel, T. Piketty, E. Saez and G. Zusman. 2017. *World Inequality Report 2018*. Paris: World Inequality Lab.

Brand, U. 2016. 'How to get out of the multiple crisis? Contours of a critical theory of social-ecological transformation'. *Environmental Values* **25** (5): 503-525. https://doi.org/10.3197/096327116X14703858759017

Burkett, P. 2006. *Historical Materialism: Marxism and ecological economics*. Leiden: Brill.

Burkett, P. and J.B. Foster. 2006. 'Metabolism, energy, and entropy in Marx's critique of political economy: Beyond the Podolinsky myth'. *Theory and Society* **35** (1): 109-156. https://doi.org/10.1007/s11186-006-6781-2

Burkett, P. 2003. 'The value problem in ecological economics: lessons from the physiocrats and Marx'. *Organization & Environment* **16** (2): 137-167. https://doi.org/10.1177/1086026603016002001

Daly, H.E. and J. Farley. 2011. *Ecological Economics: Principles and Applications*. Washington, DC: Island Press.

Douai, A. 2009. 'Value theory in ecological economics: The contribution of a political economy of wealth'. *Environmental Values* **18** (3): 257-284. http://dx.doi.org/10.3197/096327109X12474739376415

Fletcher, R. and C.F. Rammelt. 2016. 'Decoupling: A key fantasy of the post-2015 sustainable development agenda'. *Globalizations* **14** (3): 450-467. https://doi.org/10.1080/14747731.2016.1263077

Forrester, J.W. 1995. *Counterintuitive behaviour of social systems*. Cambridge: Massachusetts Institute of Technology.

Foster, J.B. 2015. 'Marxism and ecology: Common fonts of a great transition '. *Monthly Review* **67** (7): 1-13. https://doi.org/10.14452/MR-067-07-2015-11_1

Foster, J.B. and P. Burkett. 2008. 'Classical Marxism and the second law of thermodynamics'. *Organization & Environment* **21** (1): 3-37. https://doi.org/10.1177%2F1086026607313580

Foster, J.B. and P. Burkett. 2018. 'Value Isn't Everything'. *Monthly Review* **70** (6): 1-17. https://doi.org/10.14452/mr-070-06-2018-10_1

Georgescu-Roegen, N. 1970. 'The economics of production'. *The American Economic Review* **60** (2): 1-9. https://www.jstor.org/stable/1815777

Georgescu-Roegen, N. 1971. *The Entropy Law and the Economic Process.* Cambridge: Harvard University Press.

Georgescu-Roegen, N. 1993. 'The Entropy Law and the Economic Problem'. In H.E. Daly and K.N. Townsend (eds), *Valuing the Earth: Economics, Ecology, Ethics*, pp.75–88. Cambridge: Massachusetts Institute of Technology Press.

Giampietro, M. 2019. 'On the Circular Bioeconomy and Decoupling: Implications for Sustainable Growth'. *Ecological Economics* **162** (August 2019): 143-156. https://doi.org/10.1016/j.ecolecon.2019.05.001

Goodwin, R.M. 1967. 'A growth cycle'. In C.H. Feinstein (ed), *Socialism, Capitalism and Economic Growth*, pp.54–58. Cambridge: Cambridge University Press.

Gowdy, J. and S. Mesner. 1998. 'The evolution of Georgescu-Roegen's bioeconomics'. *Review of Social Economy* **56** (2): 136-156. https://doi.org/10.1080/00346769800000016

Harvey, D. 2011. *Reading Marx's Capital with David Harvey.* Video: http://davidharvey.org/reading-capital/ (accessed January 20, 2018).

Harvey, D. 2017. *Marx, Capital and the Madness of Economic Reason.* London: Profile Books.

Heinrich, M. 2004. *An Introduction to the Three Volumes of Karl Marx's Capital.* New York: Monthly Review Press.

Jalee, P. 1977. *How Capitalism Works.* New York: Monthly Review Press.

Kallis, G. 2018. *Degrowth*. Newcastle upon Tyne: Agenda Publishing.

Kallis, G. and E. Swyngedouw. 2018. 'Do bees produce value? A conversation between an ecological economist and a Marxist geographer'. *Capitalism Nature Socialism* **29** (3): 36-50. https://doi.org/10.1080/10455752.2017.1315830

Keen, S. 2013. 'A monetary Minsky model of the Great Moderation and the Great Recession'. *Journal of Economic Behavior & Organization* **86** (February 2013): 221-235. https://doi.org/10.1016/j.jebo.2011.01.010

Koch, M. 2012. *Capitalism and climate change: Theoretical discussion, historical development and policy responses*. New York: Palgrave Macmillan.

Koch, M. 2018. 'The Naturalisation of Growth: Marx, the Regulation Approach and Bourdieu'. *Environmental Values* **27** (1) 9-27. https://doi.org/10.3197/096327118X15144698637504

Krausmann, F., S. Gingrich, N. Eisenmenger, K.H. Erb, H. Haberl and M. Fischer-Kowalski. 2009. 'Growth in global materials use, GDP and population during the 20th century'. *Ecological Economics* **68** (10): 2696-2705. https://doi.org/10.1016/j.ecolecon.2009.05.007

Latouche, S. 2009. *Farewell to Growth.* Cambridge: Polity Press.

Le Quéré, C., R.M. Andrew, P. Friedlingstein, S. Sitch, J. Pongratz, A.C. Manning, J.I. Korsbakken, et al. 2018. 'Global carbon budget 2017'. *Earth System Science Data Discussions* **10** (1): 405-448. https://doi.org/10.5194/essd-10-405-2018

Levin, S.A. 1992. 'The problem of pattern and scale in ecology'. *Ecology* **73** (6): 1943-1967. https://doi.org/10.2307/1941447

Levins, R. 1998. 'Dialectics and systems theory'. *Science & Society* **62** (3) 375-399. www.jstor.org/stable/40403729

Levins, R. and R.C. Lewontin. 1985. *The dialectical biologist*. Harvard: Harvard University Press.

Magdoff, F. and J.B. Foster. 2011. *What every environmentalist needs to know about capitalism: A citizen's guide to capitalism and the environment*. New York: Monthly Review Press.

Maneschi, A. 2006. 'The Filiation of Economic Ideas: Marx, Schumpeter, Georgescu-Roegen'. *History of Economic Ideas* **14** (2): 105-125. https://www.jstor.org/stable/23722798

Martinez-Alier, J. 1987. *Ecological economics: Energy, environment, and society*. Oxford: Basil Blackwell.

Marx, K. 1973. *Grundrisse: Foundations of the critique of political economy.* Harmondsworth:

Penguin Books.

Marx, K. 1976. *Capital, A Critique of Political Economy, Volume One*. Harmondsworth: Penguin Books.

Marx, K. 1981. *Capital, A Critique of Political Economy, Volume Three*. Harmondsworth: Penguin Books.

Mayumi, K.T. 2017. 'Thermodynamics: Relevance, implications, misuse and ways forward'. In C. Spash (ed), *Routledge Handbook of Ecological Economics*, pp.89-98. Abingdon: Routledge.

Meadows, D.H. and D. Wright. 2008. *Thinking in Systems: A Primer*. White River Junction: Chelsea Green.

Meadows, D.H., J. Randers and D.L. Meadows. 2005. *A Synopsis: Limits to Growth: The 30-year Update*. London: Earthscan.

O'Connor, J.R. 1998. *Natural causes: Essays in ecological Marxism*. New York: Guilford Press.

Rammelt, C.F. and J. Boes. 2013. 'Galtung meets Daly: A framework for addressing inequity in ecological economics'. *Ecological Economics* **93** (September 2013): 269-277. https://doi.org/10.1016/j.ecolecon.2013.06.013

Rammelt, C.F. 2019. 'The dynamics of financial instability: simplifying Keen's Goodwin–Minsky model'. *System Dynamics Review* **35** (2): 140-159. https://doi.org/10.1002/sdr.1627

Saeed, K. 2016. *Development Planning and Policy Design: A System Dynamics Approach*, Worcester: Worcester Polytechnic Institute.

Soddy, F. 1933. *Wealth, Virtual Wealth and Debt*. London: Britons Publishing Company.

Steffen, W., K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, W. de Vries and C.A. de Wit. 2015. 'Planetary boundaries: Guiding human development on a changing planet'. *Science* **347** (6223): 1259855. https://doi.org/10.1126/science.1259855

Turner, G.M. 2008. 'A comparison of the limits to growth with 30 years of reality'. *Global Environmental Change* **18** (3): 397-411. https://doi.org/10.1016/j.gloenvcha.2008.05.001

Uehara, T., Y. Nagase and W. Wakeland. 2016. 'Integrating economics and system dynamics approaches for modelling an ecological–economic system'. *Systems Research and Behavioral Science* **33** (4): 515-531. https://doi.org/10.1002/sres.2373

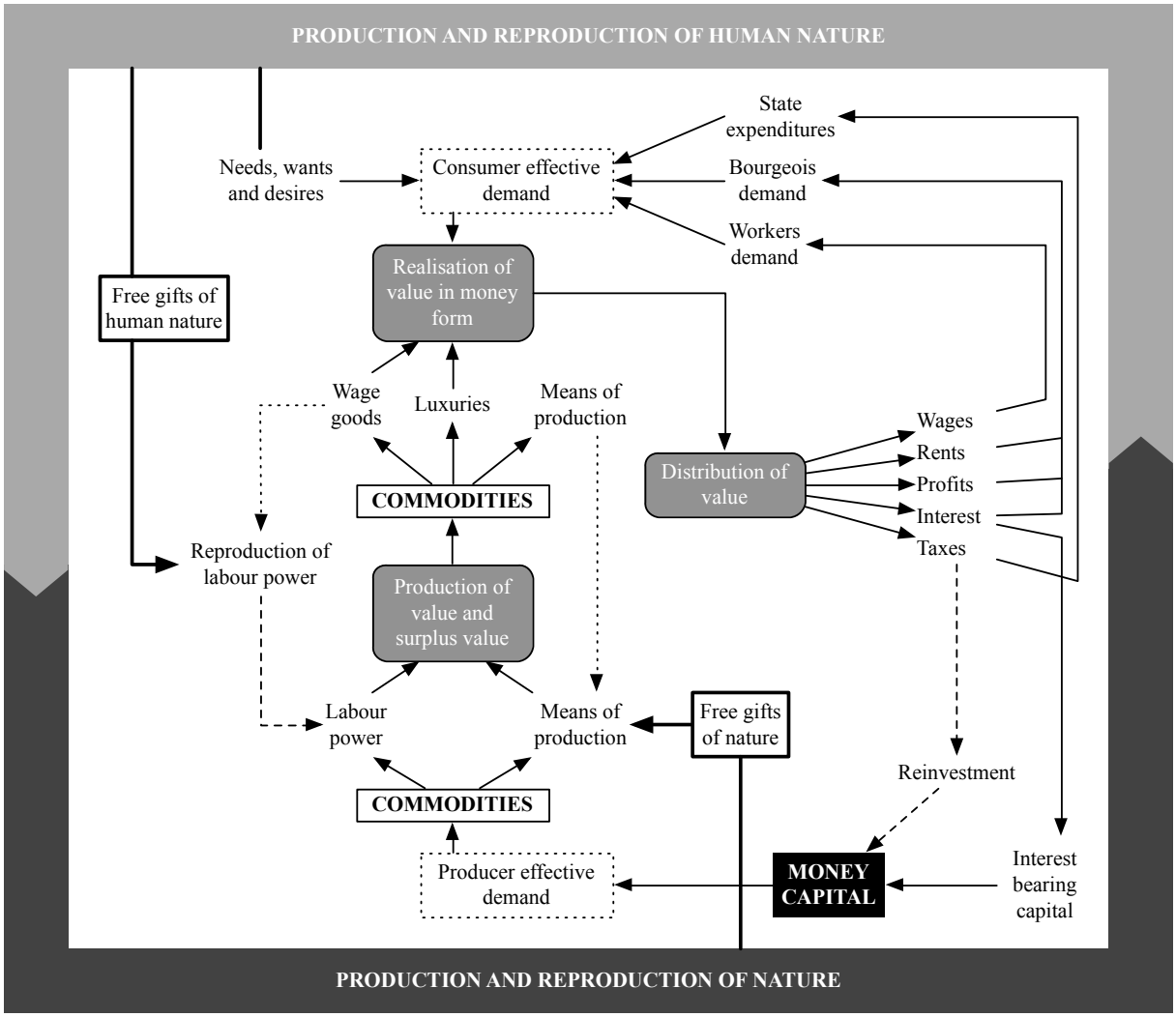


*Figure 1 - Harvey's representation of Marx's Capital (Adapted from Harvey, 2017:6, Figure 2, "The paths of value in motion as derived from the study of Marx's writings on political economy.").*

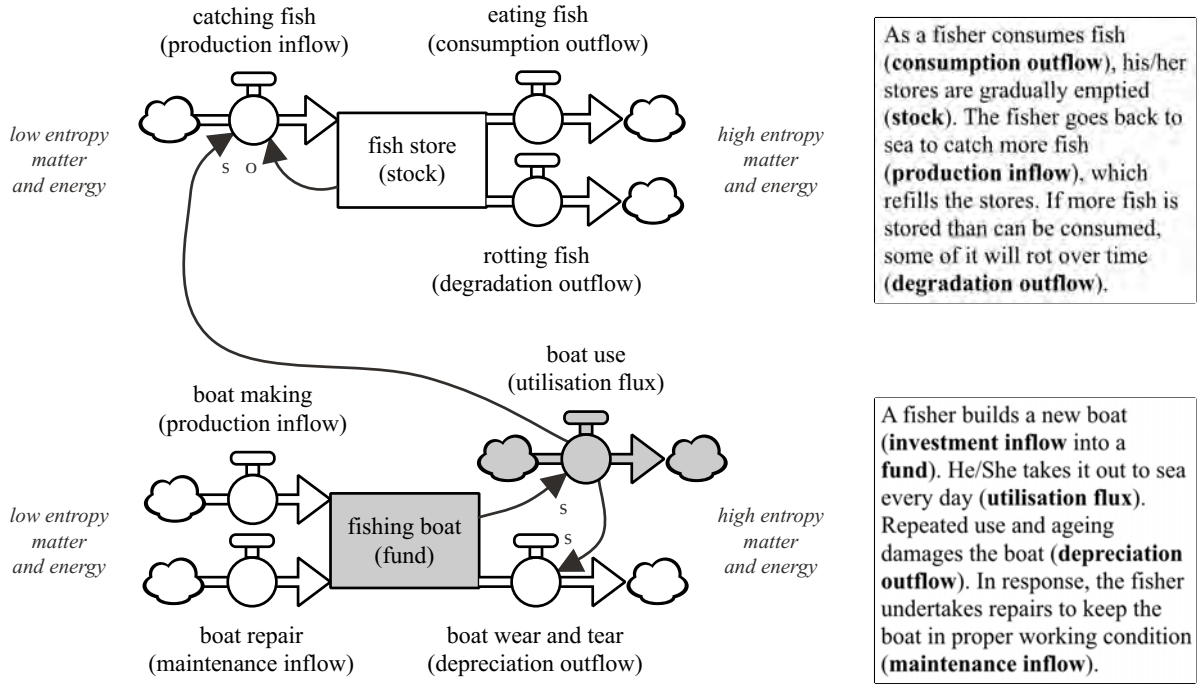


*Figure 2. Example of stocks, flows, funds and fluxes.*

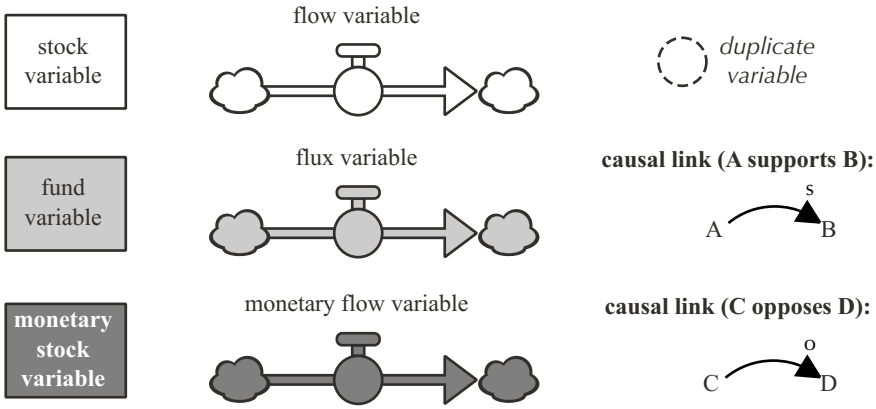


*Figure 3. Key to the diagrams.*

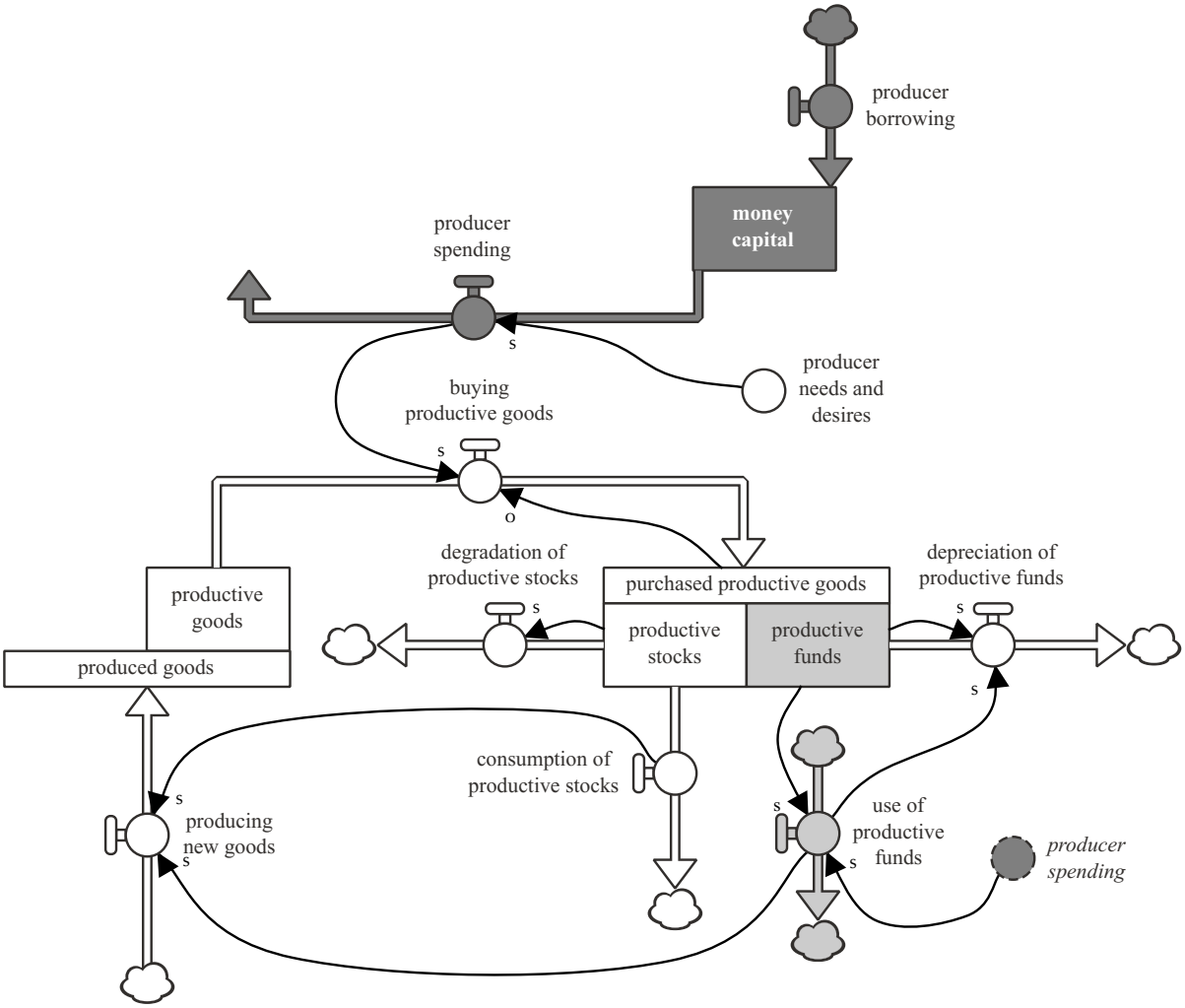


*Figure 4. Partial model: money capital, productive goods and the production of more productive goods.*

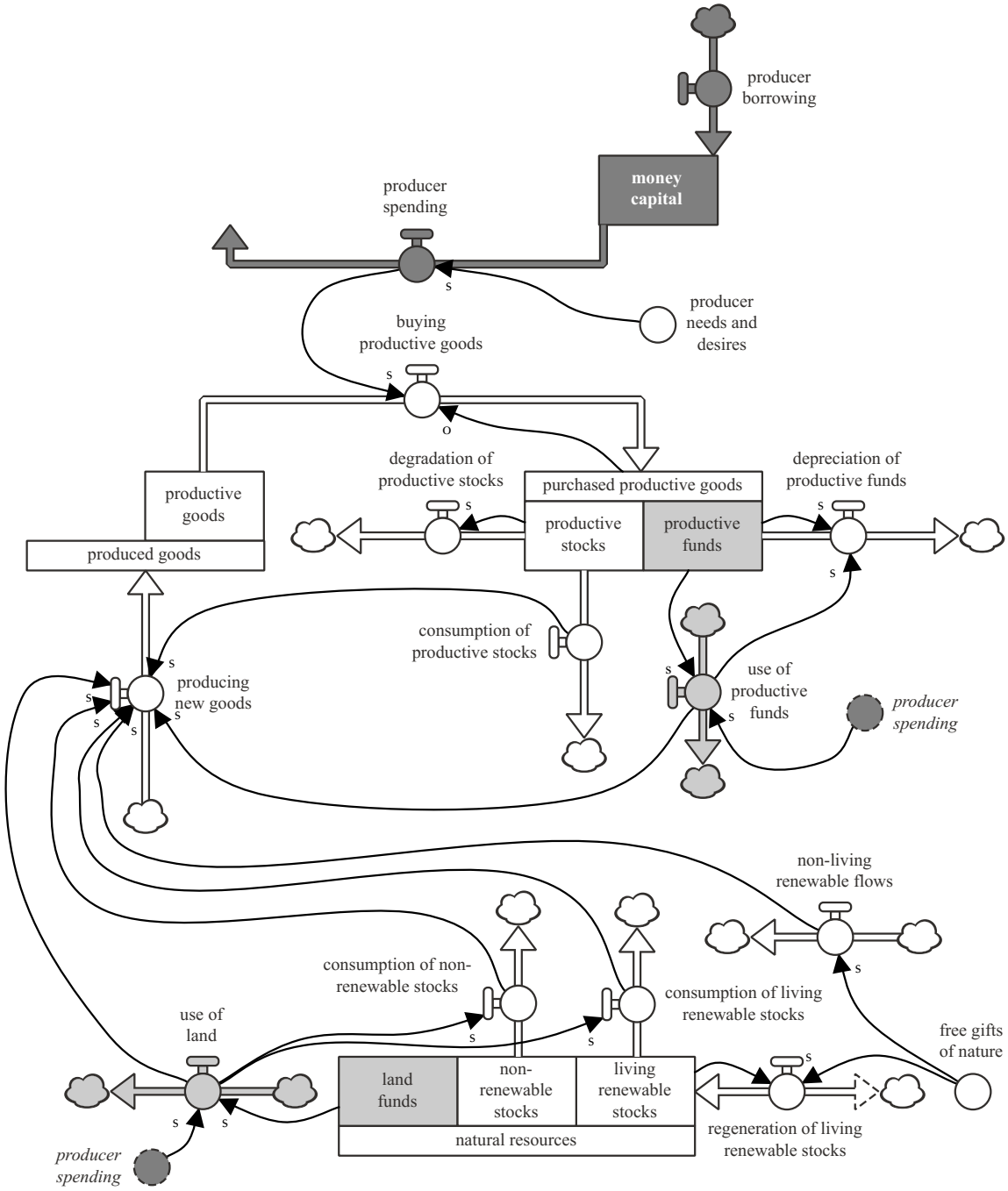


*Figure 5. Partial model: incorporating natural resources.*

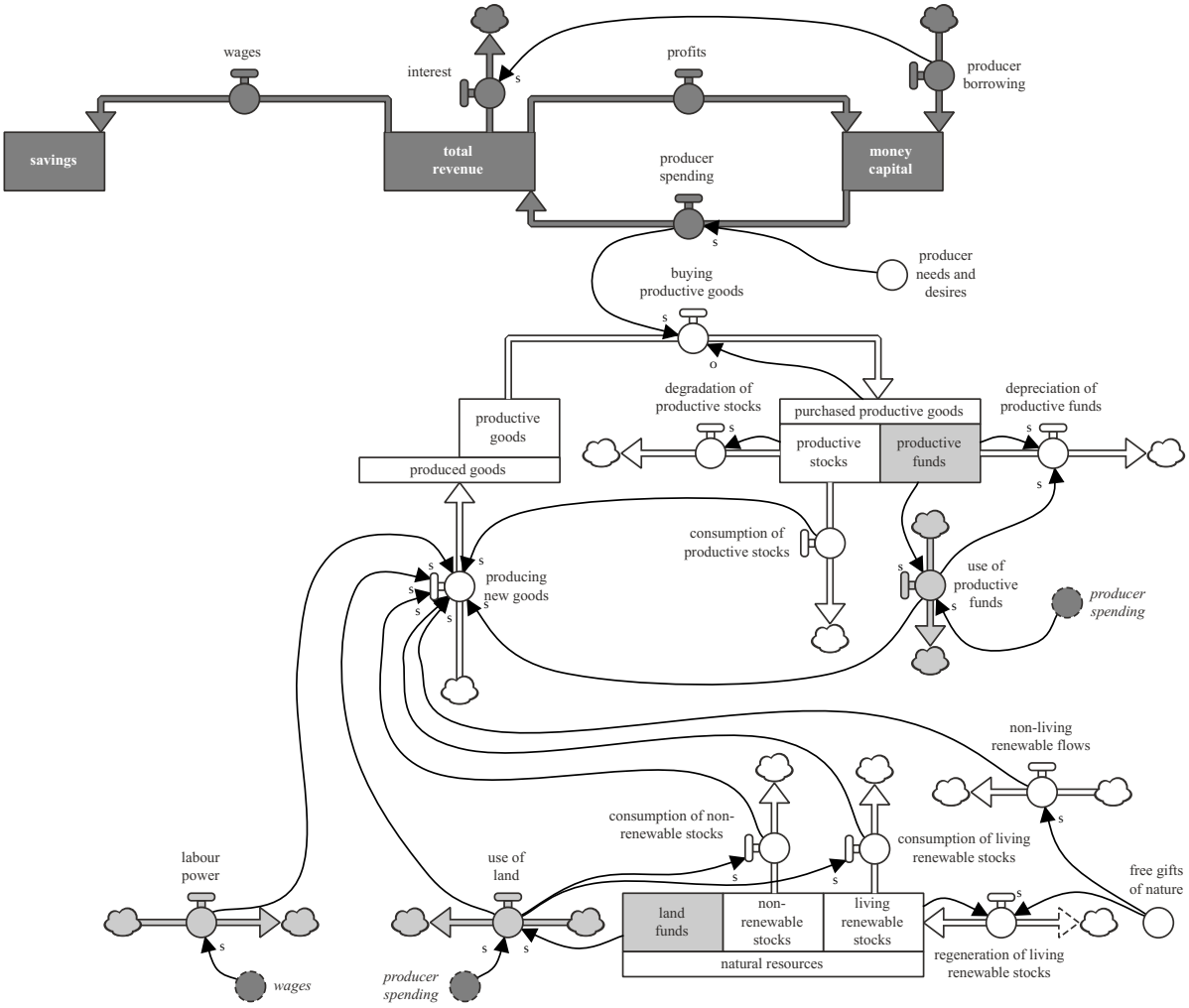


*Figure 6. Partial model: incorporating labour-power and the distribution of revenue.*

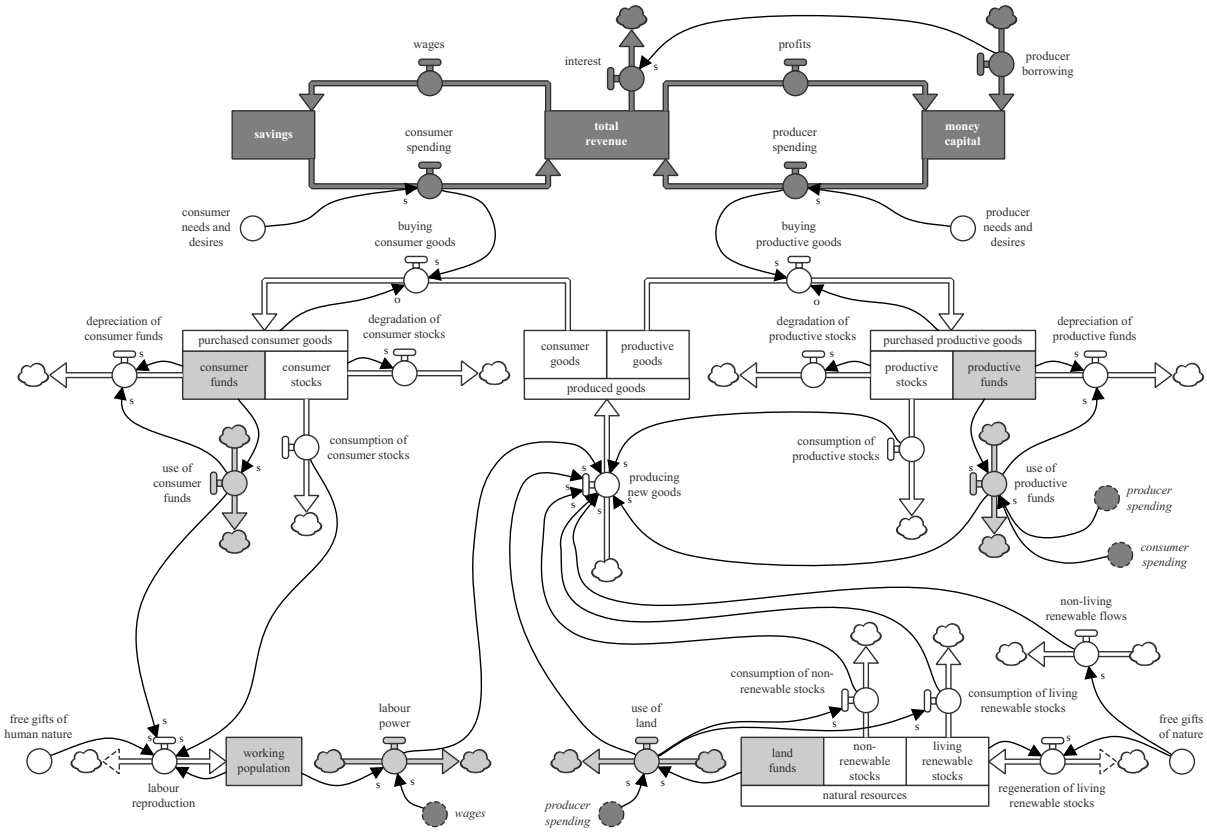


*Figure 7. Total model: incorporating consumer goods and services, and labour reproduction.*