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The Political Economy of Energy Transitions:

Marxism, Ecological Economics and the Thermodynamic Limits of Capitalism

Chapters 1-4

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CHAPTER 1 - THE THERMODYNAMIC CHALLENGE

In 1971, two years before the OPEC oil embargo brought energy issues to the forefront of global political consciousness, the Romanian-born economist Nicolas Georgescu-Roegen issued a challenge to conventional economics in his article "The Entropy Law and the Economic Problem" (Georgescu-Roegen, 1976). According to Georgescu-Roegen, both Marxist and neoclassical economic theory had failed to adequately take into account the relationship of human beings to the cycling of energy and matter in the biosphere. Because of an outlook based upon a "mechanistic epistemology" derived from Newtonian physics, Georgescu-Roegen argued that conventional economic theories couldn't come to grips with thermodynamic processes which irrevocably degrade the energy and natural resources used in the economy. As a result of their epistemological premises, neoclassical thinkers considered raw materials to be infinitely substitutable on the free market and assumed that technological innovation would provide the basis for overcoming any limit imposed by scarce resources or the problem of pollution (Barnett & Morse, 1963; Hussen, 2000). For Marxists, concerns over natural resource scarcity smacked of Malthusianism, and by the early 20th century most Marxists had drifted away from Marx's own pre-occupations with humanity's metabolic relationship with nature (Foster, 2000). As a result, most Marxist theorization on questions of capital accumulation, class struggle, and the transition to socialism tended to be divorced from any concern with how these dynamics were to the biosphere's cycling of energy and matter. Georgescu-Roegen claimed that the fundamental problem was that neoclassical and Marxist frameworks operated without taking the laws of thermodynamics – "the most economic of physical laws" into account (Georgescu-Roegen 1976: 8-9). By failing to account for the ways in which human activity is constrained due to the finiteness of low entropy resources, the inevitable loss of energy and materials to heat and friction, and the limited capacity of the planetary ecosystem to absorb the waste products which are always a byproduct of the economic process, Georgescu-Roegen argued that the conventional economic theories of both the left and the right lacked an adequate grounding in material reality.

Georgescu-Roegen's argument suggested that the remorseless and immutable laws of thermodynamics condemned all forms of industrial development to inevitable degradation – a process that was all the more certain the faster and more extensive the growth of industrialization. The only kind of economic development which Georgescu-Roegen saw as being even relatively sustainable was an economic system based upon tapping flows of renewable energy and focused on limiting and reducing its population size, use of raw materials, and the consequent output of waste. While in the long run, as Keynes put it, we will all be dead, Georgescu-Roegen argued that in the medium, humanity will be driven from its energy rich lifestyle by the inherently entropic nature of fossil fueled industrialism. As he wrote:

> Every time we produce a Cadillac, we irrevocably destroy an amount of low entropy that could otherwise be used for producing a plow or a spade. In other words, every time we produce a Cadillac, we do it at the cost of decreasing the number of human lives in the future. Economic development through industrial abundance may be a blessing for us now and for those who will be able to enjoy it in the near future, but it is definitely against the interests of the human species as a whole, if the interest is to have a life span as long as is compatible with a dowry of low entropy(Georgescu-Roegen, 1973: 46-47).

In reconsidering Georgescu-Roegen's argument some 40 years later, two things stand out. Firstly, his concerns over the depletion of low entropy fossil fuel resources and the capacity of the global environment to absorb the waste products of industrial economies appear remarkably prescient. The first decade of the new millennium has seen sharply increasing oil prices amidst growing alarm concerning the possible "peaking" of global oil production (Heinberg, 2005; Campbell, 2003; IEA, 2010). During the same time a scientific consensus has coalesced around the notion that the biosphere is reaching a "tipping point" in terms of its capacity to absorb carbon emissions. If the newly industrializing countries of the third world continue to follow the path of first world fossil fuel-based industrial development, and if first world countries do not themselves shift away from their heavy reliance on fossil fuel energies, continued carbon emissions could trigger catastrophic climate change on a global level (Hansen, 2009; Monbiot, 2007, IPCC). The ecological crisis facing humanity is apparent, and yet the economic systems Georgescu-Roegen critiqued seem to have no answer for the problem. Neoclassical economics has certainly provided few meaningful proposals for how to deal with the ecological crisis. Suggestions have been made for ways in which to marketize carbon emissions and to more thoroughly bring natural processes under the rule of the market but these have made little headway in doing anything more than creating a speculative bubble around carbon trading (Lohmann, 2006). Marxism as an ideology with any influence over actual government policy has been in precipitous decline since the collapse of the Soviet Union, and despite what has been termed a "Marx revival" in the aftermath of the anti-globalization movement and the financial crisis of 2008 (Musto, 2010), Marxism continues to struggle with developing an theoretical framework capable of addressing the global ecological crisis humanity faces.[1] The theoretical challenge that Georgescu-Roegen put forward thus remains unanswered.

The second observation arising from a re-examination of Georgescu-Roegen's concerns – many of which have been codified as principles in the discipline of ecological economics established by his students and co-thinkers – is that the critique he made of neoclassical and Marxian economics stretches back to the origins of modern economic thought itself (Burkett 2009, Kozo, 1999). The economic crisis of the 1970s produced an explosion of interest in ecological approaches to economics and led to a wide range of thinkers seeking to ground their concerns over contemporary ecological scarcity in a broader economic tradition. This led to a renewal of interest in classical political economy – most notably in its Malthusian variants – as an alternative to both neoclassical economics and Marxism.

From its emergence in the late 18th century, classical political economy was deeply concerned with the perceived inability of agricultural production to keep up with population growth. Thomas Malthus' (1766-1834) dire warnings about the 'geometric' increase of population levels are paradigmatic in this regard, but less well known are the positions of thinkers such as Adam Smith (1723-1790), David Ricardo (1772-1823) and John Stuart Mill (1806-1873) who all envisioned the agrarian capitalism of their era soon reaching a "stationary state" beyond which future growth would be impossible. Building upon the thermodynamic considerations of Nicolas Georgescu-Roegen, Herman Daly returned to the views of Smith and Mill and argued that their concept of the stationary state could provide theoretical framework for a future ecological society (Daly, 1992). Other ecological economists made a turn to the Malthusian strand of classical political economy and reintroduced the notion of "Malthusian checks" in ecological thinking – most famously in Paul Ehrlich's book *The Population Bomb* (1968) and the Club of Rome's *The Limits to Growth* (Meadows *et al.* 1972). In a similar vein, the contributions of William Forster Lloyd, a contemporary of Malthus, were picked up by the biologist Garrett Hardin, who famously used Lloyds' parable of the "tragedy of the commons" to argue that unless nature was privately valued through market mechanisms, it would inevitably be over-exploited and destroyed (Lloyd, 1832; Hardin, 1968). Hardin's influential essay helped to give rise to the notion of "natural capital" – a perspective now hegemonic in the discipline of ecological economics (Burkett, 2009: 93-114).

Perhaps the reluctance of historical materialists to engage the discipline of ecological economics over the relationship of low entropy resources to economic growth stems from the fact that the classical political economists appear as the logical forefathers of the thermodynamic framework elaborated by Georgescu-Roegen and popularized by his neo-Malthusian fellow travellers. The possibility of a fruitful exchange between Marxism and ecological economics was further diminished by the latter's adoption of the assumptions of classical political economy in its practical elaboration of Georgescu-Roegen's ideas. For if – as Daly, Hardin and Ehrlich argued – capitalist social relations were the only way of envisioning society and if problems of entropic degradation could only be resolved through market based mechanisms that left private property intact, then ecological economics would have little other alternative than to re-emerge on the terrain of neoclassical economics that Georgescu-Roegen had been so venomous in criticizing. Given the long history of Marx and Engels' battles with Malthus, (Marx and Engels, 1971) there seemed to be little reason for contemporary Marxists to seriously engage with an ecological economics that appeared as Malthusianism in drag. But the fact that ecological economics has a Smithian or Malthusian pedigree and has largely ignored the class dynamics so central to Marxism, does not let historical materialists off the hook in answering the challenge posed by Georgescu-Roegen's questioning of the role of energy in production. Even though ecological economists have greatly weakened their research program by choosing classical political economy as an analytic frame to address ecological dynamics within contemporary capitalism, the attempt by Georgescu-Roegen to integrate the science of thermodynamics with an understanding of the economic process remains the fundamental starting point for a serious investigation of the problems of energy depletion and climate change which face humanity today.

While human beings make their own history, it is an incontrovertible fact that we do so within thermodynamic limits based upon the energy resources and pollution 'sinks' available to us. The laws of thermodynamics set the parameters for humanity's metabolism with nature and combining an analysis of class struggles with an understanding of thermodynamic constraints to the flow of matter-energy in the economy holds the promise of opening up rich new fields of analysis and inquiry into understanding the past, present and future of global capitalism. The fact that the fact that the proposals of ecological economists such as Georgescu-Roegen and Herman Daly for a "zero growth" or "steady state economy" are unobtainable under a capitalist system and deeply utopian in the worst sense of the word does not mean that a socialism of the 21st-century can avoid addressing the ecological sustainability of the mode of production which will succeed capitalism. Rather, it suggests that a Marxian analysis of the "laws of motion" of capitalism and an analysis of the link between thermodynamics and class struggle under capitalism has the potential of offering tremendous insight towards not only interpreting our present ecological crisis but also transforming it. In a political context in which concerns over energy shortages and anthropogenic climate change have become pressing issues of global concern, ecological economics stands as the one of the few disciplines addressing the interrelated questions of energy use, pollution, and global political economy – subject matters that historical materialism has often been loath to tackle head-on in any comprehensive manner.

This chapter will begin by outlining the contributions of the science of thermodynamics to understanding the physical limits to economic activity within the biosphere. It will then look at Georgescu-Roegen's understanding of the economy as a subset of the biosphere, and his attempts to establish a political program to reduce the economy's consumption of low entropy stocks of energy and materials. Georgescu-Roegen's "minimum biophysical program" was further fleshed out by his student Herman Daly, who in making a return to classical political economy, built upon the concept of the "stationary state" proposed by Adam Smith and John Stuart Mill in order to arrive at a solution to what he considered to be the universal problem afflicting both capitalist and socialist economies – "growthmania" (Daly, 1992). Daly's notion of the steady-state economy – like Georgescu-Roegen's program – is inherently limited because it does not consider what kind of social agency could bring this kind of system into being, and because it does not consider the ways in which a zero growth or "degrowth" economy is fundamentally incompatible with capitalism. The failure of Daly and Georgescu-Roegen to consider the inevitable resistance of the capitalist system to any "steady-state" alternative, to understand the growth and development of capitalism in historical terms, and to come to grips with the economic logic of capitalism itself, explains part of the reason for the eclipse of their proposals. The other reason stems from the wholesale return of ecological economics to classical political economy and its methodological obsession with Malthusian population controls and the notion of "natural capital" – two tendencies which have eliminated possibilities of developing an anti-capitalist and socialist tendency within ecological economics and undermined Georgescu-Roegen's thermodynamic critique of neoclassical economics.

THERMODYNAMICS AND THE ECONOMY

> A theory is more impressive the greater is the simplicity of its premises, the more different are the kinds of things it relates and the more extended its range of applicability. Therefore, the deep impression which classical thermodynamics made on me. It is the only physical theory of universal content which I am convinced, that within the framework of the flexibility of its basic concepts will never be overthrown.
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> – Albert Einstein (quoted in Rifkin, 1980: 43)

The laws of thermodynamics were formulated in the context of the industrial revolution as English society shifted from a society based upon an organic economy – one in which the vast majority of food and industrial inputs came from locally grown agricultural inputs – to a mineral economy in which the primary sectors of accumulation were based in mining, metalworking and machine driven production (Wrigley, 1988). The outstanding provider of motive force in the later stages of this industrial revolution was the steam engine – which not only pumped water out of the coal mines, but ran trains and steamships and powered the growing factory system. The first steam engines invented by Thomas Newcomen were remarkably inefficient, and only able to outcompete horse-drawn mechanisms in pumping water from coal mines because the coal they used for their fuel was freely available at the mines where they were operating and thus cheaper than the grain required to feed the horses (Wilkinson, 1973).[2] But despite this inefficiency, steam engines had an inescapable advantage over renewable flows of energy – they could operate around the clock and in any location their fuel could be transported to. And by good fortune, England's plentiful supply of coal provided a material base for the fledgling capitalist system which had begun to develop industrial capacities in the late 18th century.

Steam power spread across Europe in the early 19th century, and in the wake of the Napoleonic wars, a French physicist by the name of Sadi Carnot – who was convinced that the main reason for France's defeat was the impact of superior British manufacturing technology – sought to understand how the efficiency of the steam engine could be improved.[3] In his groundbreaking 1824 book *Reflexion sur la puissance motrice du feu*, Carnot observed that heat always flowed from hot substances to cold ones, and showed that heat engines produced work by taking advantage of this differential in temperature. What moved the pistons was not the temperature within the boiler, but rather the temperature gradient between the hot boiler and the cooler radiator. The greater this differential, the more power could be extracted from the engine. Carnot's research identified two central propositions which would later be incorporated into the laws of thermodynamics: heat flows from hot bodies to cooler ones and never in reverse; and due to the entropic phenomenon of heat loss, a complete conversion of heat into work – a perpetual motion machine – is impossible (Schneider & Sagan, 2006: 37-38). The profundity of Carnot's observations is indicated by the fact that a new branch of physics needed to be developed as a result of his work since the laws of mechanics cannot explain a process of unidirectional movement (Georgescu-Roegen, 1971: 129).

In 1854, Rudolph Clausius – considered with Carnot to be the other cofounder of classical thermodynamics – coined the term "entropy" to measure "the one-way conversion of energy into heat and friction" (Schneider & Sagan, 2006: 44). On the basis of his research between 1840 and 1865 Clausius showed that all forms of known energy always move in a unidirectional fashion – from a higher to a lower-level – and thereby formalized the first and second laws of thermodynamics, laws which owed their elaboration to the research program on steam power unleashed by the industrial revolution (Georgescu-Roegen, 1971: 129). These laws can be framed in a variety of ways. Smil summarizes them as follows:

> Our modern understanding of energy includes a number of profound realizations: that mass and energy are equivalent; that many conversions link various kinds of energies; that no energy is lost during these conversions (this is the first law of thermodynamics); and that this conservation of energy is inexorably accompanied by a loss of utility (the second law of thermodynamics) (Smil, 1999: xiii).

The first law of thermodynamics thus dictates that the amount of energy and matter in the universe remains constant, and is neither created nor destroyed, although it can be transformed into different forms. The second law of thermodynamics, the entropy law, states that the total entropy in the universe is always increasing toward a maximum. In this sense, the transformation of matter and energy is always unidirectional "...from usable to unusable, or from available to unavailable, or from order to disorder. In essence, the second law says that everything in the entire universe began with structure and value and is irrevocably moving in the direction of random chaos and waste" (Rifkin, 1980: 6).

From an economic standpoint, what is so significant about the laws of thermodynamics is that they call into question the mechanistic notions of consumption and production hegemonic to the discipline. Indeed, "in scientific terms, there is no phenomenon called production, only transformation. No matter how energy or resources are used, scattered, or dispersed, their sum remains essentially the same, as dictated by the Law of Conservation of Matter and Energy" (Hawken et al, 1999: 148). While this notion has a long history in philosophy – and was expounded upon by the Greek philosopher Epicurus, the 18th century economist Petro Verri [4] and Karl Marx[5]among others, the notion was largely evacuated from 20th century economic thought (Altvater, 1993: 189-190). There are significant – and deeply pessimistic – implications to conceptualizing economic processes in entropic terms. Because all forms of metabolic interchange rely upon the "order or quality – the structure, concentration, or purity of matter," the quality of low entropy fuels and materials is of vital importance for the maintenance of a living system – whether we are talking about simple biological processes or advanced industrial economies (Hawken et al., 1999: 148). However, in the conversion of low entropy energy and resources in the economic process, the laws of thermodynamics dictate that some amount of energy and materials will always be dissipated and lost. As T. Randolf Beard and Gabriel Lozada put it:

> The economic process is one in which stocks of some things are depleted, while stocks of other things accumulate. Things depleted include propitiously situated, useful material substances, while things accumulated include toxic byproducts of industrial activity. Except for trivial quantities of metals, say, lost due to spacecraft launches, the actual amount of copper on Earth is today the same as it was one million years ago. What has changed in the interim is how, and in what forms, that copper is distributed in the environment (Beard & Lozada, 1999: 4).

Production is thus an irreversible process which turns high-quality low entropy materials and energy into waste. This process can only continue as long as there are suitable supplies of low entropy materials and energy, and available "sinks" which can absorb the various forms of pollution which are an inevitable byproduct of the economic process. The "free gifts of nature" which have played such an important part in the material development of human culture, become inevitably degraded, dispersed, and diminished over time.

On the cosmic level, as well as here on earth, as every second passes there is less free, unbound, available energy that is capable of doing work. This is "Time's arrow" the unidirectional increase in the amount of entropy and disorder as the universe approaches an ultimate state of heat death or "thermodynamic equilibrium" (Georgescu-Roegen, 1999: 198-200). While the human species will be long extinct billions of years before the universe reaches thermodynamic equilibrium, and while much entropic degradation (such as the cooling of the Earth's core or the gradual decline in the sun's output of energy) is minimal over the lifespan of the human species, this degradation can be easily measured in localized systems deprived of an ongoing input of energy. In the experiments of classical thermodynamics:

> …all motion usually comes to a standstill very soon as a result of various kinds of friction; differences of electric or chemical potential are equalized, substances which tend to form a chemical compound do so, temperature becomes uniform by heat conduction. After that the whole system fades away into a dead, inert lump of matter. A permanent state is reached, in which no observable events occur. The physicists call this the state of thermodynamic equilibrium, or of "maximum entropy" (Schrodinger 1944, 70).

This entropic tendency is less obvious in thermodynamically "open" systems (ones in which low entropy energy can enter and waste products can leave) or in thermodynamically "closed" systems such as the Earth's biosphere which receives and dissipates large amounts of low entropy solar radiation but exchanges negligible amounts of matter with the surrounding solar system. Because of the Earth's thermodynamically closed nature, there are only a finite amount of low entropy energy resources and minerals on the Earth's crust which can be used in the economic process, although the flow of solar energy remains largely untapped. The laws of thermodynamics remind us of two other factors which limit the use of low entropy resources. Because of the unidirectional tendency towards increasing entropy, complete recycling of low entropy resources is impossible (see Beard and Lozada, 1999: 103-107). Secondly, the earth's biosphere has only a finite capacity to absorb pollution. Until the Industrial Revolution, both of these issues were moot as the capacity of the human species to either use up available low entropy resources or impact the biosphere on a global level was constrained by our technological development. However, with the growth of industrial capitalism over the past 200 years, the global human appropriation of "net primary production" has soared to previously unimaginable levels. Studies indicate that at the present moment some 83% of the global terrestrial biosphere is under "direct human influence," while over one third of the Earth's productive surface is "entirely dominated" by humanity (Haberl et al. 2010).

The edifice of classical thermodynamics developed by 19th century scientists such as Carnot and Clausius did not consider complex thermodynamically open systems such as the Earth's biosphere. Instead, they were narrowly focused upon experiments taking place within isolated systems, such as steam engines. The reactions they studied took place in heatproof containers, and the endpoint of the processes was an equilibrium state where no further change in the system was possible (Schneider & Sagan, 2006: 26). This approach earned classical thermodynamics a reputation as a 'dismal science' since experiments inevitably ended up in the unchanging state of maximum entropy described by Schrodinger. But beginning in the middle of the 20th century, a new approach to thermodynamics began to be developed – that of net equilibrium thermodynamics – which studied the flow of energy across open systems, and which examined the metabolism of living creatures with their surroundings.

This approach received much of its initial impetus from Schrödinger's famous 1943 lectures in Dublin, Ireland. His lectures were focused on addressing the paradox of how living creatures appeared to contradict the laws of thermodynamics. Life's defiance of the entropy law is evident in the way in which life forms resist entropic degradation by producing nearly identical reproductions of themselves over generations, while also avoiding "the decay of atomic chaos mandated by the second law of thermodynamics" over the course of their own life spans (Schneider & Sagan, 2006: 15). How lifeforms were able to fight off the second law of thermodynamics so they lived in a state far from thermodynamic equilibrium was not addressed by classical thermodynamics.

Schrodinger resolved this seeming paradox by arguing that living organisms keep themselves from thermodynamic equilibrium only by virtue of constantly consuming low entropy resources and expelling high entropy waste into the surrounding environment. Life temporarily defeats the second law of thermodynamics by creating a higher level of entropic disorder in its surrounding environment through the process of metabolism.

> How does the living organism avoid decay? The obvious answer is: By eating, drinking, breathing and (in the case of plants) assimilating. The technical term is metabolism.... Every process, event, happening – call it what you will; in a word, everything that is going on in nature means an increase of the entropy of the part of the world where it is going on. Thus a living organism continually increases the entropy – or, as you may say, produces positive entropy – and thus tends to approach the dangerous state of maximum entropy, which is death. It can only keep aloof from it, i.e. alive, by continually drawing from its environment negative entropy – which is something very positive as we shall immediately see. What an organism feeds upon is negative entropy. Or, to put it less paradoxically, the essential thing in metabolism is that the organism succeeds in freeing itself from all the entropy it cannot help producing while alive. (Schrodinger 1967, 75-76).

Schrodinger's description of the struggle of life to gain low entropy fuel and avoid high entropy waste is at the root of Georgescu-Roegen's critique of mainstream economics. For ecological economists, the macro level processes by which the economy metabolizes with the surrounding environment are analogous to the micro level processes in which an organism metabolizes with its environment in order to stay alive. Both are subject to the same thermodynamic laws and constraints. As Herman Daly put it:

> All life processes and all technological processes work on an entropy gradient. In all physical processes matter-energy inputs in their totality are always of lower entropy than the matter-energy outputs in their totality. Organisms cannot survive in a medium consisting of their own final output. Neither can economies. Like nature's technology, man's technology is strictly confined within the laws of thermodynamics (Daly, 1992: 22).

Schrodinger's lectures influenced the development of a school of net equilibrium thermodynamics which sought to understand the development of ecosystems through an analysis of the flow of energy. Thinkers such as Howard T. Odum (1924-2002), Eugene P. Odum, (1913-2002) and Alfred Lotka (1880-1949) described the ways in which organisms metabolized with their environment and built complicated organizing structures to degrade low entropy resources. In the same way that the heat engines studied by classical thermodynamics produced work based on the energy gradient between hot and cold, living organisms maintained themselves by feeding upon a variety of energetic gradients present in the biosphere. These insights were to play a profound role in the development of the discipline of ecological economics and to offer hopes for the reconciliation of the historic split between social and physical sciences. Georgescu-Roegen hoped that his work would result in the developing of a new field of economics – which he called "bioeconomics" – by combining "economics, thermodynamics, biology, anthropology, sociology and political science in a whole intended to provide a basis for useful discussions of the "best aims and means for mankind" (Beard & Lozada, 1999: 4-5). [Need more material here on Lotka and Odum.]

THE CONTRIBUTIONS OF NICOLAS GEORGESCU-ROEGEN

What Schrödinger did for thermodynamics in biology, and H.T. Odum did for thermodynamics in ecology, Nicholas Georgescu-Roegen did for thermodynamics in economics. Nicolas Georgescu-Roegen is best known for his work in linking economic phenomena to biophysical processes and is widely considered one of the key theoreticians and founders of ecological economics (Røpke, 2004). Born in 1906 in Romania, Georgescu-Roegen was a talented mathematician who studied at the University of Bucharest before completing a dissertation at the Institut de Statistique at the Sorbonne in Paris. Georgescu-Roegen's transition from statistician to economist came after he accepted a fellowship at Harvard University in 1933 where he was mentored by Joseph Schumpeter and worked with such other leading intellectuals as Wassily Leontief, Edgar M. Hoover, Frank Taussig, Oskar Lange and Paul Sweezy (Mayumi & Gowdy, 1999: 4). Georgescu-Roegen's intense intellectual activity under Schumpeter's guidance was central in leading him to develop a dialectical analysis of economic phenomena which recognized the profound importance of qualitative transformations in economic processes.

Georgescu-Roegen's magnum opus was his book *The Entropy Law and the Economic Process*, written in 1971. In this wide-ranging work he developed the perspective that the laws of thermodynamics were intimately related to the economic process. All economic processes require low entropy inputs and have as their ultimate result the degradation and disordering of the matter-energy used as a raw material, along with the enjoyment of the particular good or service produced. Low entropy materials are highly ordered structures that have come into being as the consequence of larger expenditures of energy – be it of heat, pressure, gravitational forces, etc. As Georgescu-Roegen's student and ecological economist Herman Daly noted, low entropy resources are the prerequisites for any economic process.

> Low-entropy matter/energy is a physical coordinate of usefulness, the basic necessity that humans must use up but cannot create, and for which the human economy is totally dependent on nature's services. Entropy is a qualitative difference that distinguishes useful resources from an equal quantity of useless waste (Daly, 1999: 80).

Low entropy resources are essential for life and to the continued metabolism of all living creatures. The single most important source of this low entropy is the sunlight which plants capture through photosynthesis, and which they use to produce sugars and capture carbon in the process of building highly ordered structures. In turn, plants are eaten by herbivores higher up the trophic chain who are themselves eaten by carnivores. Humans are not exempt from this process for we exist in a metabolic relationship with the rest of nature, drawing in low entropy matter from plants and animals to be transformed into chemical energy, and emitting waste – in the form of body heat, excrement and most obviously since the Industrial Revolution, through the products and by-products of the production process (Delanda, 2000).

Central to the successful evolutionary strategy of human beings was the development of what Georgescu-Roegen calls "exosomatic organs" which gave human beings an evolutionary advantage by allowing for the increased consumption of low entropy resources.

> The human species found a far speedier way of becoming more powerful in numberless directions. It began to produce detachable limbs – exosomatic organs – instead of waiting to acquire them by biological mutation.... With exosomatic evolution, the human species became addicted to the comfort provided by detachable limbs, which, in turn, compels men to become the geological agent who continuously speeds up the entropic degradation of the finite stock of mineral resources (Georgescu-Roegen, 1976: xiv).

From the broad ax to the plow, the tractor to the transport truck, and the steam engine to the nuclear power plant, these "detachable limbs" put human beings in a class of our own when it comes to our relationship to nature and the rate at which we consume low entropy resources. Georgescu-Roegen's analysis provides important insights about the ways in which human society is transformed based upon the appropriation of energy resources. He argued that there were three key "Promethean" technologies that transformed the development of humanity – fire, agriculture, and the steam engine. What made an innovation "Promethean" for Georgescu-Roegen is that it had "the property of being self-sustaining as long as fuel supply continues" and thereby was "marked by a qualitative conversion of energy and produced an irreversible change in the relationship between humans and nature, causing profound alterations in natural ecosystems and human societies" (Mesner & Gowdy, 1999: 57-58).

The use of fire enabled human beings to not only move into colder climates and to light up their dwelling places after nightfall, but also to be able to access new food resources by cooking and preserving food. The development of agriculture in the Neolithic revolution saw human beings domesticate plant and animal species and thereby acquire access to new stores of caloric energy and means of motive power. The "exosomatic organ" acquired by humans in this process was the ruminant's stomach, which allowed humans to transform cellulose indigestible to us into edible milk or meat.

The most significant "Promethean revolution" that Georgescu-Roegen identified was the invention of fossil fuel powered heat engines which transformed agrarian societies based upon the appropriation of solar flows of energy (wind and water power, and the products of organic agriculture) into industrial societies based upon the rapid and increasing consumption of finite stocks of low entropy fossil fuels. The use of these stocks of fossil fuels allowed humanity to exceed the energetic budget determined by the flow of solar energy and renewable resources and represented the development of a qualitatively different kind of human civilization. The shift to stocks of fossil fuels also gave industrial societies greater leeway in overcoming ecological bottlenecks. If pre-industrial human societies upset the metabolic balance in which they lived with their surrounding environment, they soon felt the consequences of their actions. As a result, particular customs arose to regulate the human metabolism with the environment.[6] In contrast, the new fossil fuel-based industrial societies marshalled powerful exosomatic forces which allowed for the creation of a truly global market – one which was able to compensate for the degradation of local ecological conditions by drawing in new and previously unexploited resources from distant ecosystems (Pomerantz, 2000; Altvater 1993).

The renowned economist Paul Samuelson compared Georgescu-Roegen's model of the economy to an hourglass "whose sands run downward as the arrow of time advances: an irreversible process that admits of no permanently renewable steady-state for maintainable economic consumption" (Samuelson, in Kozo 1999: xiv). The incorporation of fossil fuels into the economy drastically increased the size of the passage through which the sand flows through the hourglass, enabling construction of fantastic new structures. However, as Georgescu-Roegen reminds us, an increased flow of energy based on finite stocks of low entropy fuel cannot be maintained indefinitely, and in fact shortens the overall lifespan of the human species.

> The economic process, like any other life process, is irreversible (and irrevocably so); hence, it cannot be explained in mechanical terms alone. It is thermodynamics, through the entropy law, that recognizes the qualitative distinction which economists should have made from the outset between the inputs of valuable resources (low entropy) and the final output of valueless waste (high entropy) (Georgescu-Roegen, 1976: 8-9).

Eventually, the availability of finite stocks of low entropy resources will "peak" and then decline, and the economy will collapse once these resources have been used up or when the waste produced from economic processes overwhelms the capacity of ecosystems to absorb it. Industrial civilization has accomplished all manner of wondrous feats – it has sent men to the moon and spacecraft to the edge of our solar system, built buildings half a kilometer high, and established a system of international air travel linking the globe – but for Georgescu-Roegen, these accomplishments are inherently transitory ones. The faster the throughput of energetic and low entropy material resources, the more likely it is that we will fall victim to the pollution we produce and the quicker humanity will return to an energy budget determined by the flow of solar energy.[7]

A sudden decline in the energy available to a complex industrial society is likely to have significant social effects. As the anthropologist Joseph Tainter pointed out, societies use increasing flows of energy and raw materials in order to increase their level of complexity as a way of dealing with social conflict and ecological limitations.

> in many crucial spheres, continued investment in sociopolitical complexity reaches a point where the benefits for such investment begin to decline, at first gradually, then with accelerated force. Thus, not only must the population allocate greater and greater amounts of resources to maintaining and evolving society, but after a certain point, higher amounts of this investment will yield smaller increments of return (Tainter, 2004: 92).

Tainter claimed that the problem with growing social complexity is that at a certain point the benefits of further complexity and energy use cannot address the problems they were intended to solve. Diminishing returns may be made up for by shifting to a new and more productive energy regime – a new Promethean revolution – but failing such an innovation the end result will be a forced return to a situation of lower social complexity (Tainter, 2004: 193-203).

As an alternative to the abrupt and systemic crisis that he thought would be produced by a continued high throughput of low entropy resources, Georgescu-Roegen suggested that the most thermodynamically sound type of social and economic organization was small-scale village production, based upon the solar flows of energy rather than on fossil fuel stocks. As he wrote, "...the logical panorama for the future of mankind is a radical de-urbanization with most people practicing organic agriculture on family farms and relying on wood for fuel and many materials, as in the traditional villages" (Georgescu-Roegen, 1976 xviii). In an attempt to bridge current day reality with the arrival of his peasant-based utopia, Georgescu-Roegen put forward what he termed a "minimum biophysical program" to aid in this transition. The program began with a demand that the global armaments industry should be shut down immediately in light of the tremendous energetic and material resources that it wasted. With resources diverted from weapons production, a large-scale transfer of wealth and knowledge to the Third World could then be undertaken in order to improve the quality of life and to reduce population growth. A process of sustained de-urbanization led by a rapid transition towards organic agriculture free from fossil fuel inputs could ensure adequate food inputs for the human population. Energy efficiency would be dramatically increased and the wastage of energy through over-heating, over-cooling and speeding would be eliminated.

"Extravagant gadgetry and unnecessary fashion" would be prohibited, with innovation centred instead upon the production of easily repairable, durable consumer goods. In sum, social priorities would be shifted from endless accumulation and consumption towards the enjoyment of what philosophers since Aristotle have termed the "good life" (Georgescu-Roegen 1976: 30-35).

Georgescu-Roegen's utopian political framework was spurned by bourgeois economists and politicians as well as most socialists. Not only did Georgescu-Roegen's program call for the end of economic growth per se and thus require the end of continued capital accumulation, but he seemed to have no notion of how his recommendations would play out in terms of class struggles, and no idea about what social force could overcome the tremendous power of the military-industrial complex, the oil industry, agribusiness, and the advertising industry who would all no doubt be actively opposed to his program. The question of what kind of state would be needed to enforce restrictions on economic growth and wastefulness similarly went unaddressed. His conclusion seemed to be that since it was patently obvious that the economy could only grow to a certain size before it ran out of low entropy resources or the biosphere's capacity to absorb waste, at some point technocrats and politicians if not the general public as a whole would come to embrace his perspective. Resigned to the fact that such a possibility was unlikely, Georgescu-Roegen mused fatalistically that "perhaps the destiny of man is to have a short but fiery, exciting, and extravagant life rather than a long, uneventful, and vegetative existence. Let other species – the amoebas, for example – which have no spiritual ambitions inherit an earth still bathed in plenty of sunshine" (Georgescu-Roegen, 1976: 35).

Despite his significant earlier contributions to mainstream economics, recognized by among other things, his status as a Distinguished Fellow of the American Economic Association, Paul Samuelson's praise of him as "a scholar's scholar, an economist's economist," and his presence in books such as Mark Blaug's *Great Economists Since Keynes* – Georgescu-Roegen died frustrated that mainstream economics did not engage with his arguments concerning the thermodynamic limits to growth (Daly, 1999: 13). As Blaug put it, Georgescu-Roegen's critiques of neoclassical economics "…have been respectfully received and quickly put away. For various complex reasons, not to mention the difficult style in which they are written and the intimidating references they contain to theoretical developments in physics and biology, these works have received virtually no critical discussion from economists" (Blaug, 1985, p.71-72). While frustrated, Georgescu-Roegen was under no illusion as to the reasons for his marginalization. When Herman Daly once asked him why neoclassical economists at MIT refused to engage with his work, Georgescu-Roegen replied with an old Romanian proverb: "in the house of the condemned one must not mention the executioner" (Daly, in Gowdy 1999: 14).

ECOLOGICAL ECONOMICS TURNS TO CLASSICAL POLITICAL ECONOMY

With his contributions largely ignored by both neoclassical and Marxist economists, it fell to an eclectic medley of environmental activists, heterodox economists, and assorted academics to carry Georgescu-Roegen's insights into the new discipline of ecological economics which took form in the decade before his death in 1994. Unfortunately, Georgescu-Roegen's successors not only lacked much of his intellectual rigour, scientific aplomb, and capacity for advanced mathematics, but shared his political tendencies towards Malthusianism. Few anti-capitalists saw much premise in extending his work to the typical concerns of the left, perhaps because he only suggested vague and idealist alternatives to market-based society.[8] In the larger school of ecological economics, some like Robert Costanza, attempted to develop an "embodied energy theory of value" along Sraffian lines, which Georgescu-Roegen was strictly opposed to (Costanza, 1980; Georgescu-Roegen, 1979). Others, like his student Herman Daly, were much closer to his outlook on thermodynamics, but even then, were at odds with him on issues such as the viability of maintaining a "steady-state" society over the long term. In a sense, the marginalization of Georgescu-Roegen from within the discipline that he was so central in founding is unsurprising, as the conclusions that he offered were so dismal, his concepts for making social change so limited, and his intellectual work so hard to follow (Beard & Lozada, 1999). However, to understand Georgescu-Roegen's legacy, we need to take account of the rise of ecological economics and its attempt to grapple with some of the central problems that he identified.

As Inge Røpke has noted in his assessment of the early history of modern ecological economics, the late 1970s and early 1980s saw a coming together of a variety of different disciplines focusing on questions of energy, economics and ecology (Røpke, 2004). The impacts of the 1973 and 1979 oil crises convinced many that a new era of ecologically determined limits to growth had arrived. This debate around resource scarcity was anticipated by Barnett and Morse's book *Scarcity and Growth* in 1963, but took off a few years later with the publication of Paul Ehrlich's book *The Population Bomb* in 1968 and with the release of Meadows et al's book *The Limits to Growth* in 1972. Ehrlich raised the spectre of a catastrophic Malthusian crisis caused by population increases that would result in the deaths of "hundreds of millions of people" in the 1970s and 1980s irregardless of any "crash programs embarked upon now" (Ehrlich, 1978: xi). In a more empirical vein, the Club of Rome, a research group established by powerful business interests largely based in Europe, commissioned a group of scientists and researchers to make projections of current trends in economic growth. Using newly introduced computing systems, these researchers studied past trends in population growth, industrialization and consumption of nonrenewable resources. They concluded that if population levels and economic growth were not strongly curtailed, "the most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity" (Meadows et al, 1974).

The debates over population growth, raw materials and energy shortages, the intellectual contributions of Georgescu-Roegen and Juan Martinez-Alier[9] on the relationship of energy to economic processes, and the influences of HT Odum's analysis of the role of energy in ecology led a grouping of academics to develop a discipline of economic thought that sought to cross the borders of the natural and social sciences. They called this new discipline ecological economics "because it implies a broad, ecological, interdisciplinary, and holistic view of the problem of studying and managing our world" (Costanza, 1989: 1). Key influences on the field included biologists such as Rachel Carson, Barry Commoner and Paul Ehrlich, physicists such as Robert Ayers, systems ecologists such as H.T. Odum and Robert Costanza, and economists such as Kenneth Boulding, Nicolas Georgescu-Roegen, and Herman Daly (Røpke, 2004: 298-302). A core grouping of researchers including Herman Daly and Robert Costanza from the United States, Juan Martinez-Alier from Spain and AnnMari Jansson from Sweden were the main initiators of the series of meetings that resulted in the formation of the International Society for Ecological Economics in 1988 and the launch of the peer-reviewed journal *Ecological Economics* in 1989 (Røpke, 2004: 305).

In its early stages ecological economics critiqued both neoclassical and Marxian economics, arguing that despite their fundamental disagreements both shared a fundamentally problematic analysis of natural resources and humanity's relationship to the biosphere. The crux of the matter is that ecological economics argued that the economy needed to be seen as a subset of the biosphere, and that economic growth was thus inherently limited. Neoclassical economics held that the definition of what constituted a "natural resource" was inherently capable of change. As a given resource became depleted, prices for it would rise, thereby stimulating the search for substitute resources or technological innovations which would allow for greater efficiency in the use of existing stocks of that resource (Lomberg, 2004). Marxists shared a similar perspective, as Bukharin argued in his *Historical Materialism*:

> "Raw materials" according to Marx are products of labor, and they have as little existence in the bowels of nature as has a painting by Raphael or Herr Cunow's waistcoat…. [A] certain stage of technology must have been reached before wood, or, fibers, etc., may play the part of raw materials. Coal becomes a raw material only when technology has developed so far as to delve in the bowels of the earth and drag their contents into the light of day. The influence of nature, in the sense of providing materials, etc., is itself a product of the development of technology; before technology had conquered coal, coal had no "influence" at all. Before technology with its feelers had reached the iron-ore, this iron-ore was permitted to sleep its eternal slumber; its influence on man was zero (Bukharin, 2002).

The conclusion of this line of thinking, consistent in both neoclassical economics and Marxism is that technological solutions, whether initiated by price signals or by the liberation of technology from the fetters placed upon it by the capitalist mode of production could overcome any serious problem of scarcity. The counter from ecological economics was that because the economic process was fundamentally about the creation of entropy and waste – as the inevitable byproduct of production – and because the limits of the biosphere were finite, even if a constant stream of new natural resources could take the place of those which had been previously depleted, the end result would be an even more thoroughly polluted world and the destruction of the ecological systems which provide us with the "free gifts of nature." The only alternative would be to reduce economic growth and to shrink the economy – anathema to both neoclassical economics and Marxism which held that continued economic development and a rise in living standards across the world required the global extension of the industrial revolution.

In this context, actually existing socialism appeared as a poor cousin to the industrial capitalism with which it competed. Marxism could be seen as a path to industrial development in countries where the indigenous capitalist class was too weak or too much under the thumb of imperialism to successfully follow the Western capitalist road to development through import substitution, high tariffs, and a state-sponsored nation-building program. Instead of Marxism winning the support of the working class of advanced capitalist countries, it was utilized by middle-class intellectuals in Third World countries oppressed by imperialism to overthrow the comprador bourgeoisie and their nations and to rapidly industrialize themselves. Once this basic level of industrialization had proved successful, and as it was clear that these bureaucratic and commandist societies were incapable of developing the high technology associated with the later stages of the industrial revolution, elites in these societies opened their doors to economic integration with the West as in the case of the former USSR and China. Consequently, ecological economists tended to see "actually existing" forms of socialism as simply representing an alternative route to an industrial growth-based system with little concern for the environment or ecological questions.

The collapse of the alternative model of development pioneered by the Soviet Union freed ecological economics from any pressing need to engage with socialist theory. The failure of ecological economics to relate to Marxism was compounded by the failure of most Marxists to engage with the questions and concerns raised by ecological economics. As Paul Burkett notes, a review of "the English-language political economy journals in which Marxists have a prominent and ongoing presence… reveals an almost equally complete vacuum of serious Marxist engagements with ecological economics as a meta-paradigmatic discipline" (Burkett, 2009: 4). The favour was returned by ecological economics:

> …a thorough survey of Ecological Economics, the discipline flagship journal, starting from its initial number in 1989, revealed that Marxists had a near zero presence in it. In fact, the Journal had carried only two articles espousing even a remotely Marxist perspective. Apart from these two articles, the Journal contained a few other references to Marx and Engels, and to Marxism in general, but these are almost always in the way of polemical, ad hominem dismissals which – despite the discipline's commitment

> to methodological pluralism – expressed blanket denials of the actual or potential usefulness of Marxist thinking for economic-ecological analysis (Burkett, 2009: 4).

And yet despite its critiques of neoclassical and Marxian economics, the founders of ecological economics wanted to make ecological economics a multidisciplinary field, which sought to bridge the gap between conventional economics and ecological concerns. There was also a broad-based agreement that the central problematic that ecological economics sought to address was the fact that all major economic paradigms, including capitalist, socialist, and “mixed systems,” were based upon the framework of “continuing and unlimited” growth – a technical impossibility given thermodynamic limits (Costanza, 1989: 2). Because the discipline lacked its own distinct methodological approach to understanding economic processes, early responses to the problem of “growthmania” tended to take two different approaches. The first was to call for a “conscious methodological pluralism” in the hopes of overcoming the inherent difficulties of understanding the interplay of economics and ecology across scale, time, place and discipline (Norgaard, 1989). This approach saw the field of ecological economics itself as a type of ecosystem in which different methodological approaches would compete with each other and evolve to fill the different niches requiring explanation. However, this call for pluralism was at best a deferment of the question of methodology.

As the field matured, the need for a theoretical grounding became evident. The most common approach, which would soon became dominant, was to make a wholesale return to classical political economy, where, it was argued, writers such as Adam Smith, Thomas Malthus, John Stuart Mill and David Ricardo had developed an ecologically aware “materials-based approach to production and prices” that was methodologically distinct from neoclassical economics (Christensen, 1989). Because classical political economy continued to be identified with the framework of liberal, competitive capitalism, it seemed to offer relatively safe ground from which to mount a critique of neoclassical economics especially in the wake of the collapse of the Soviet Union and Fukuyama’s declaration of the victory of liberal democracy as the “end of history” (Fukuyama, 1992) Moreover, when the work of the classical political economists was examined through an ecological lens, it became evident that questions of resource depletion and biophysical limits were central to the observations of these theorists. In the days of Smith, Ricardo and Malthus, machines were powered by renewable energy flows such as wind or water, or more often, by animal or human power. The main source of heat energy for both economic processes and for domestic consumption came from wood, which had to be grown on land which was then unavailable for growing food. Advances in economic growth and development were closely linked to agricultural productivity, the cultivation of new lands, or by means of an increased division of labor – so-called “Smithian growth.” But because the energetic basis of agrarian societies is so limited, the spectre of "diminishing returns" haunted the classical political economists. “Smithian growth” was limited by “Malthusian checks,” and the classical economists envisioned that capitalist growth and development would enter a "stationary state" in which no further growth was possible. It is this gloomy outlook on the long-term future of economic growth that earned classical political economy the sobriquet "the dismal science" and that galvanized ecological economists to embrace its methodology.

While a certain amount of respectability could be gained by laying claim to the legacy of these well-known thinkers, ecological economics failed to grapple with the problem that classical political economy was rooted in explaining and defending the interests of the large landowners and emerging capitalist class which had gained political prominence in England in the 18th and 19th centuries (McNally, 1988). As a result, classical political economy was based upon a series of normative assumptions about capitalist dynamics which have undermined ecological economics as a potentially emancipatory framework for social change.

In particular, the fixation of ecological economics with the classical political economy of Thomas Malthus painted the discipline into a corner. By taking Malthus outside of his political context and painting him as a proto-environmentalist rather than a ruling class apologist concerned to justify the powers and privileges of the large landholders (Ross, 1998), ecological economics severely limited its own frame of analysis. Writing in the context of a counterrevolutionary movement opposed to the radical egalitarianism of the French Revolution, Malthus consistently argued that poor people "had no claim of right on society for the smallest portion of food, beyond that which his labor would fairly purchase" (Malthus, 1809: 394).

Malthus didn't see the poverty and hunger of large numbers of people as a social problem. Instead, he viewed hunger as a necessary and effective means for directing labor into the factories of the Industrial Revolution. As Eric Ross has pointed out, Malthus "...not only suggested that the fertility of the poor was the main source of their poverty, but implied that it was actually best if that fertility was not significantly controlled by human intervention, because that would reduce poverty and with it the chief stimulus for the poor to seek work" (Ross, 1998: 4). Malthus was opposed to the use of contraceptives or sexual techniques which reduced fertility, even though he was aware that these techniques could reduce population growth significantly. Malthus's political arguments were suited to the interests of the ruling elite of the day since "…his so-called law of population acquitted the property-owning class of any such accountability, by arguing that poverty was the "natural" product of the fertility of the poor, rather than that of the social or economic system. The solution therefore was a matter of individual, not systemic, responsibility" (Ross, 1998: 5). As a result of the services he rendered, Malthus was granted the first chair in political economy at an English university.

Because ecological economists such as Georgescu Roegen did not develop a theory of capitalism or an analysis of an alternative social and economic system which could replace it, they fell back on Malthusian positions, arguing that Malthus was right to see population growth (as opposed to the social and economic system underling production and consumption) as the primary factor stressing the Earth's carrying capacity and the well-being of society. As Georgescu-Roegen put it:

> The explosive pressure of population within this finite planet – on which the classical economists based their pessimistic prognosis – can no longer be subject to doubt. There is no longer another America or Australia to provide a safety valve for population pressure... and the sad story is that the present rate of production does not suffice to maintain even the present population at the floating nutritional line. (Georgescu Roegen, 1976, xii-xiii)

Georgescu-Roegen was hardly alone among modern ecological economists in seeing population growth as a fundamental problem facing humanity. Paul Ehrlich, the author of the best-selling book *The Population Bomb* – despite having seven children himself – campaigned enthusiastically for government sterilization programs and the closing of US borders to immigrants. Garrett Hardin, a leading ecological economist, was opposed to food aid for Ethiopia during its famine in the late 1980s, arguing that providing food would only increase the size of the population which would then suffer further hardship in the future. In an article for Psychology Today in 1974, entitled "Lifeboat Ethics: The Case Against Helping the Poor," Hardin approvingly quoted Alan Gregg – a vice president of the Rockefeller foundation – who opposed the development of higher yield crops in the so-called "green revolution" because it enabled further population growth in the third world. As Hardin noted, Gregg "likened the growth and spread of humanity over the surface of the earth to the spread of cancer in the human body," adding that "cancerous growths demand food; but, as far as I know, they have never been cured by getting it" (Hardin, 1974). Malthusianism is a dead end for ecological economics. It ignores the underlying social relations responsible for increasing or decreasing population rates, and it is all too often deployed in racist or eugenicist ways.

Ironically, it was the embracing of classical political economy by ecological economics that was largely responsible for the eclipse of Georgescu-Roegen's critique of industrialism. Instead of developing a nuanced analysis of the thermodynamic processes which constrained all forms of the human metabolism with nature, and linking this analysis to an examination of the social contradictions of class-based societies, what instead developed was a framework based on crude Malthusian fears of Third World population growth and the development of a theory of "natural capital" which while professing to save nature from over-exploitation, opened the way to the complete and total commodification of all natural resources in a return to neoclassical economics.

Because of the turn to classical political economy, an interrogation of the relationship between class struggles, modes of production, state formations and their relationship to specific "energy regimes" was effectively closed off. Consequently, ecological economics has tended to embrace a "vulgar" political economy which appropriated classical political economy's assumptions of man as a rational interest maximizing agent, assumed capitalism as a "natural" and permanent economic system, and ignored the possibility that class struggle could transform capitalist property relations in a democratic and socialist direction. Ecological economists made no attempt to engage with Marx's well-known critique of the classical political economy that they had embraced, and they failed to examine the ideological suppositions informing the discipline itself. The inherent problems with the turn of ecological economics to classical political economy can be clearly seen in the examination of the way that Herman Daly sought to extend John Stuart Mill's notion of the steady-state, and the way in which Garrett Hardin framed his notion of the "tragedy of the commons."

HERMAN DALY AND THE STEADY STATE

> The growth paradigm has outlived its usefulness. It is a senile ideology that should be unceremoniously retired into the history of economic doctrines.... Political economy must enter a period of revolutionary science to establish a new paradigm to guide a new period of normal science. Just as mercantilism gave way to physiocracy, physiocracy to classical laissez-faire, laissez-faire to Keynesianism, Keynesianism to the neoclassical growth synthesis – so the current neoclassical growth mania must give way to a new paradigm. What will the new paradigm be? I submit that it must be very similar to an idea from classical economics that never attained the status of a paradigm, except for a brief chapter in John Stuart Mill's Principles of Political Economy. This idea is that of the steady-state economy.
>
> – Herman Daly (1973: 152)

One of the foremost theorists of the emerging discipline of ecological economics was Georgescu-Roegen's former student Herman Daly. As an economist in the World Bank critical of the econometric analysis of his neoclassical colleagues, Daly sought to create the framework for a political economy consistent with the thermodynamic principles elaborated by Georgescu-Roegen. One of Daly's most significant contributions was to return to Adam Smith and John Stuart Mill's notion of a "stationary state," in which continued economic expansion had come to an end, and to suggest that the concept could be applied to resolve contemporary capitalism's ecological crisis. Reframing the concept as a "steady state economy," Daly defined it as:

> ...an economy with constant stocks of people and artifacts, maintained at some desired, sufficient level by low rates of maintenance "throughput," that is, by the lowest feasible flows of matter and energy from the first stage of production (depletion of low entropy materials from the environment) to the last stage of

> consumption (pollution of the environment with high entropy waste and exotic materials) (Daly, 1992: 16).

The notion of zero growth that Daly propounded did not mean that life in the steady-state economy would be 'nasty, brutish and short.' If natural resources were primarily used for the building of renewable energy infrastructure, tools and machines were designed for functionality and longevity, wealth was more evenly distributed, and overall population levels were lowered, then there would be more than enough resources to meet everyone's needs and it should be possible for all to enjoy the "good life" promoted by philosophers from Aristotle to Henry David Thoreau (Daly, 1982: 22). Moreover, while the use of physical materials would be limited in a steady state system, the nonphysical attributes of daily existence could continue expanding infinitely, as the "immaterial flux" that Daly and Georgescu-Roegen defined as the true marker of "value" in the economic process – people's own sense of personal happiness and fulfillment, their enjoyment of leisure time, or their spiritual enlightenment – were not subject to the same thermodynamic limits as those of a "consumer society." Daly compared a steady state economy to the biological processes of an old growth forest at its "climax" – entropy production would be minimized and the capture and use of the solar gradient would be maximized.[10] In developing his analysis Daly drew on insights from the emerging school of systems ecology, referencing Eugene P. Odum's insight that "young ecosystems seem to emphasize production, growth, and quantity, whereas mature ecosystems emphasize protection, stability, and quality" (Daly, 1973: 20).

Daly's notion of the "steady state" was derived from the widely held notion of the "stationary state" that classical political economists such as Adam Smith, David Ricardo, Thomas Malthus, and John Stuart Mill deemed to be inevitable following the early expansive stages of agrarian capitalism. These thinkers – living as they did in the era before widespread use of fossil fuels and the Industrial Revolution[11] – did not believe that the economy could continue to expand indefinitely. Instead, they held that after going through an expansionary or "progressive" stage, capitalism would inevitably culminate in a steady or "stationary" state in which profits and wages would be reduced to a minimum, and where landowners would gain the lion's share of societal surplus (Smith, 1999; Ricardo, 1817, Mill, 1987).

It is worth mentioning that classical political economists like Adam Smith didn't see the newly emerging capitalist markets as a qualitatively new and distinct form of social organization. Unlike a historical materialist approach which analyzes class societies on the basis of how and in what way economic surplus is "pumped out of the direct producers," (Marx, 1984: 791; Wood, 2002) Smith saw societies across time and space as having universal economic dynamics arising from common impulses to "truck, barter and trade" (Smith, 1999: 117-121). In making comparisons between such disparate societies as Britain, China, India and the British colonies of North America, Smith argued that the happiness and well-being of the society was directly related to the stage of economic growth that it found itself in – be it progressive, stationary, or declining. As Smith put it:

> ...it is in the progressive state, while the society is advancing to the further acquisition, rather than when it has acquired its full complement of riches, that the condition of the labouring poor, of the great body of the people, seems to be the happiest and the most comfortable. It is hard in the stationary, and miserable in the declining state. The progressive state is in reality the cheerful and the hearty state to all the different orders of the society. The stationary is dull; the declining, melancholy (Smith, 1999: 197).

In the progressive stage marked by a rapid expansion of population onto available fertile lands, wages and profits would be high. But high wages would depress profit margins and give an impetus to the labouring class to reproduce itself more quickly. As available land was occupied and opportunities for agricultural growth became more limited, wages would sink and the competition between capitalists would reduce profits to a minimum while a growing population would depress the wages of labor. This was to be the inevitable end of the agrarian capitalist system that Smith examined. The future of England, or the American colonies could be seen in the stationary states of Holland or China with their "full complement of riches which the nature of the soil and climate, and its situation with respect to other countries, allowed it to acquire" (Smith, 1999: 197). Accordingly, the social class which would ultimately benefit the most was the landlord class which controlled the land from which all raw materials and food came from.

Interestingly, in returning to classical political economy to borrow the concept of the steady-state, Daly didn't seem to recognize the ecological underpinnings of the concept as it was developed by Smith and Mill. Daly argued that the steady-state is necessary:

> not for the reasons given by classical economists who saw increasing rent and interest eliminating profit and thus the incentive for "progress." Rather, the necessity follows immediately from physical first principles. The world is finite, the ecosystem is a steady-state (Daly, 1973: 152-53).

Ironically, Daly failed to pick up on the ecological thinking of the classical political economists, who were actually acutely aware of the limits of growth in the predominantly agrarian economies of their day. The capitalist economy studied by the classical political economists such as Adam Smith, David Ricardo, Thomas Malthus, and John Stuart Mill, was a preindustrial system that had an intrinsically limited flow of inputs and outputs on a finite land base. Because land, labor, and capital were all considered to be essential factors of production, if any one factor was lacking, classical political economists argued that continued growth would be impossible and that the "law of diminishing returns" would set in. In the preindustrial organic economy, the most serious obstacle to growth was the limited availability of the land to provide raw materials for capital and subsistence for labor. The historian and demographer E.A. Wrigley reminds us of the absolute centrality of agriculture to this era:

> ...land was not simply the principle source of food for the population, but also virtually the sole source of the raw materials used in industrial production. Those not employed in agriculture were chiefly engaged in processing animal or vegetable products. Spinners and weavers, fullers and dyers; tanners and curriers; tailors and shoemakers; sawyers, coopers, carpenters and cabinetmakers: trade such as these made up the bulk of industrial employment. Wool, flax, silk, cotton, hides, leather, hair, fur, straw, wood: these were the prime raw materials and manufacturing industry. The building industry was less exclusively confined to organic raw materials than most others, but remained heavily dependent on wood. Wood was also the prime source of the heat energy needed in innumerable industrial and domestic activities (Wrigley, 1988: 18).

Because of the limited capacity of the land to produce raw materials needed for continued economic growth, the more that the economy grew, the harder it became to ensure further growth. This was the basis for the "law of diminishing returns," or as Wrigley put it, a "negative feedback loop" which actively undermined the possibilities for further growth (Wrigley, 1988, 29-31). Mill, who of all classical political economists, wrote the most on the stationary state, argued that the central problem – which affected industry as well as agriculture – was one of diminishing returns from increasing production on a limited land-base. As Mill put it:

> The materials of manufacture being all drawn from the land, and many of them from agriculture, which supplies in particular the entire material of clothing; the general law of production from the land, the law of diminishing return, must in the last resort be applicable to manufacturing as well as to agricultural history. As population increases, and the power of the land to yield increased produce is strained harder and harder, any additional supply of material, as well as of food, must be obtained by more than a proportionally increasing expenditure of labor (Mill, 1987: 185).

Although classical political economists did not put their analysis of the stationary state in thermodynamic terms, the problem they identified was one of the limited availability of low entropy materials and energy. In an era in which the raw materials used in manufacturing came almost completely from local agrarian production, Mill's conception of the diminishing law of returns expressed a real sense of biophysical limits. As Wrigley notes:

> Quite apart from the depressing implications of the principle of declining marginal returns for living standards in an organic economy, such an economy was necessarily severely inhibited by its energy budget. Just as raw materials were almost all organic, both heat and mechanical energy were obtained from organic sources, the heat energy from burning wood (or its derivative

> charcoal); the mechanical energy from human or animal muscle (Wrigley, 1990: 5-6).

At the same time, it is important to note that while the approach of classical political economists to the stationary state was sensitive to underlying ecological factors it was by no means an "objective" accounting of all of the possibilities open to humanity, but rather a projection based upon keeping particular social relations intact. The concept that capital or labor could eliminate the rent going to the landlords, or even that a non-exploitative social system could be established was never considered as a possibility.

Although British colonies produced important raw materials that helped to increase the total available land base under cultivation, transporting bulky raw materials before the advent of the railway and steamship in the mid-1800s was costly and inefficient. A large merchant fleet did exist, but shipping was limited both by the availability of wood to build the ships, the problem that wooden boats could only be built to relatively small dimensions, and the fact that they could only travel at the speed that the wind blew them. The impact of the industrial revolution on the production, consumption and transportation of foodstuffs and raw materials – and the relief it provided to the ecological pressure on English agriculture – cannot be underestimated. The rapid spread of steam power technology which enabled the creation of railroads and oceangoing steamships capable of transporting large quantities of bulky commodities quickly and cheaply from one end of the world to the other fundamentally transformed the relationship between land, labor and capital and overcame worries about the arrival of the stationary state and the problem of diminishing returns.

Even if he didn't consider the stationary state envisioned by Smith and Mill to have emerged from a consciousness of ecological limits, Daly did think that the notion could be an effective solution to overcoming the "growthmania" of both capitalist and socialist models of economic growth. However, this would mean that the discipline of economics would have to return "to its moral and biophysical foundations" by replacing the "mechanistic methods of physics... [with] value-based thinking in the mode of classical political economy" (Daly, 1992: 3-4). Moral values of restraint, stewardship, humility and holism needed to prevail over simple desires to maximize profitability. While the concept of holding value-based thinking above market imperatives may seem to resonate with a socialist outlook, Daly was quick to insist that he was not seeking to eliminate the role of market-based systems. Instead, he proposed the establishment of three basic "institutions" which would "build on the existing basis of the price system and private property and [which] are thus fundamentally conservative" (Daly, 1992: 51). The three institutions that Daly suggested were a "distributist institution" to enforce "minimum and maximum limits on income and a maximum limit on wealth;" a system of transferable birth licenses that would restrict population growth while also selling procreative rights on the market; and the introduction of a system of depletion quotas for the use of raw materials which would reduce the throughput of materials through the economy.

Out of these three institutions, the distributist framework seemed to be the most radical and anti-capitalist, but Daly was quick to point out that his purpose in limiting maximum income and ensuring a minimum income was to ensure the continued legitimacy of capitalism. As he notes, “without some such limits, private property and the whole market economy lose their moral basis, and there would be no strong case for extending the market to cover birth quotas and depletion quotas as a means of institutionalizing environmental limits” (Daly, 1992: 53-54). Because market exchange between the powerful and the powerless “can easily be a mask for exploitation,” limits on maximum income and wealth will ensure that exchange relations between relative equals will be “mutually beneficial.” In arguing for the limiting of wealth to what can be “individually” accumulated over one lifespan, Daly drew upon the classic concepts of private property and market relations established by John Locke, the founding fathers of the American Constitution, and by later political economists such as John Stuart Mill. He envisioned a small-scale capitalist system in which property can only be acquired through personal effort and fair dealing, is relative to human need, and is controlled and directed by the individual in question (Daly, 1992: 55). In short, Daly argued for the return to an idealized neo-Smithian capitalism which if it ever existed has long since been displaced by the growth of monopoly capitalism.[12]

According to Daly's plan, once individuals reach the maximum income bracket, a 100% marginal tax rate would come into effect and the wealthy would then devote their time to non-economic pursuits. Daly also imagines that having fixed minimum and maximum incomes would result in the elimination of class conflict and structures of working class self organization:

> Why conspire to corner markets, fix prices, and so forth, if you cannot keep the loot? As for labor, the minimum income would enable the outlawing of strikes, which are rapidly becoming intolerably exploitative of the general public. Unions would not be needed as a means of confronting the power of concentrated wealth, since wealth would no longer be concentrated (Daly, 1992: 55-56).

Daly does not seem to realize that to impose real limits on wealth and income, to break up the massive multinational corporations, eliminate the inheritance of private fortunes, while simultaneously freeing labor from the discipline of hunger and want, would call into question the very existence of the capitalist system. To be successfully implemented, his program would require the all out waging of class war and would raise the question of the struggle over state power. Nor for that matter does Daly consider how capitalism could be disciplined in such a way as to put up with this enforced equality, or what kind of political and state formations – let alone popular social movements – would be required to bring this plan into action.

Daly’s other institutions, the transferable birth licensing system and the depletion quota appear to be slightly more feasible under capitalism, but pose the question of how much state interference in the personal lives of citizens should be countenanced. His birth licensing system would work by issuing all women “an amount of reproduction licenses that corresponds to replacement fertility.” The original distribution of the licenses would happen on an egalitarian basis, but because an exchange of licenses is permitted, the market would reallocate birthing rights “efficiently.” As Daly notes, his system “frankly recognizes that reproduction must henceforth be considered a scarce right and logically faces the issue of how best to distribute that right and whether and how to permit voluntary reallocation” (Daly, 1992: 59).[13]

The depletion quota would operate by limiting aggregate use of low entropy resources. Daly envisions a two-tiered market for all resources. The government would auction limited quota rights to resource buyers who would then be authorized to purchase from resource sellers. Prices for resources would rise, and the higher priced resources would “empower more efficient and frugal use of resources by both producers and consumers. Thus the windfall rent from higher resource prices would be captured by the government and become public income” (Daly, 1992: 59). Daly thought his plan would lead to increased efficiency, limit depletion, and would also reduce pollution. Of course, it would also likely lead to inflation and capital flight from any country that took the initiative to implement it, but Daly does not touch on these questions. The central problem to be faced is again the question of class power. How to force large multinational mining corporations to willingly pay more for access to depletion quotas and how could this kind of taxation regime be implemented on a coordinated basis worldwide? The creation of binding global agreements limiting the capacity of capital to employ resources as it wishes is a whole other area of regulation left undiscussed by Daly.

In neoclassical economics, the phenomenon of economic growth plays a central role in diffusing class conflict. If the “economic pie” is constantly getting bigger – Adam Smith’s “progressive state” – then the pressures for the redistribution of wealth can be lifted, as all classes will get richer, even if the share going to the rich increases the most. Daly’s “steady state” approach directly challenges this conception and requires a halt to the growth of this pie, and even a shrinking of it – something that would necessitate a redistribution of wealth, or at least the sharpening of class conflict which could no longer be postponed by a constantly growing economy.

Like Georgescu-Roegen’s program for deindustrialization, Daly’s conception of the steady-state is profoundly lacking in any kind of practical insights about how it could be achieved. Because he saw the solution as lying in the extension of market dynamics to new sectors of human life, Daly did not identify what kind of political force in society could produce the needed transformation, and had no conception of the necessary role of state action or popular class struggles in redistributing its access to the stocks and flows of wealth between social classes and rich or poor nations. One obvious direction in which he could have looked for inspiration was in a variety of Marxist or socialist traditions which sought to limit or supersede the rule of the market. However, Daly was quick to rule out any consideration of the relevance of Marxism to this question, stating that:

> It would be far too simpleminded to blurt out "socialism" as the answer, since socialist states are as badly afflicted with growthmania as capitalist states. The Marxist eschatology of the classless society is based on the premise of complete abundance; consequently, economic growth is exceedingly important in socialist theory and practice. Also, population growth, for the orthodox Marxists, cannot present problems under socialist institutions. (Daly, 1973: 23.)

These few words are the extent of Daly's political engagement with Marxism on the question of the steady-state, and each point that he makes is wrong. Firstly, the socialist tradition and the insights of Marxism cannot be reduced to the practices of 20th-century "actually existing" socialist countries as Daly does here. While it is undoubtedly true that the rapid push towards industrialization by the former Soviet Bloc and China produced environmental catastrophes, there was initially a lively debate along ecological lines within Russia about how the transition to industrialism should best take place (Foster, 2000: 241-245). These discussions came to an end after Stalin purged both the right and left opposition within Russia, but they did point to the existence of a range of alternative approaches within a socialist framework for development. The path to industrialization that Stalin ended up following was not compelled by some abstract "growthmania" inherent to socialism and identical to capitalist imperatives of growth, but was largely determined by the need to compete militarily with the threat of capitalist invasion and encirclement. Production was not geared towards the endless consumption of consumer goods, but rather towards military ends (which proved essential in defeating Nazi Germany in World War II) and towards the production of capital goods necessary for industrialization in a predominantly peasant society (Parenti, 1997).

For all of their flaws, the kind of state planning used by actually existing socialist countries offers an alternative framework to markets and the profit motive in determining the speed and flow of material and energetic inputs to the economy. Attempts to build socialism in desperately poor and underdeveloped countries ravaged by civil war and foreign occupation have no doubt contributed to the inefficiencies, bureaucratic distortions and lack of democratic process involved in such "actually existing" socialism, but the failure of the "communist hypothesis" to date does not constitute proof that socialism cannot arise within advanced capitalist countries or that socialist politics cannot produce democratic institutions to collectively regulate production in the overall interests of humanity (Badiou, 2010). Even if many 20th century socialist experiments seem anachronistic in the wake of the collapse of the Soviet Union, some such as the Cuban model, offer insights into ways in which ecological problems can be successfully addressed outside of market frameworks.[14]

Socialism is an economic system based upon the use of societal resources to meet human needs rather than to produce profits for the wealthy. Its basic eschatology is not "complete abundance," but rather an end to the domination of one class by another, the socialization of wealth, and the establishment of democratic structures to ensure the rule of the working class in the transition to a classless communist society (Draper, 1977; Mésázros, 2008). Given the severity of the ecological crisis currently facing humanity, there is no reason to assume *a priori* that the "free association of producers" that Marx equated socialism to, would not be able to reorganize production to minimize entropic flow while democratically meeting the needs of people in their society.

Contrary to Daly's suggestion that socialists didn't seriously address the question of population growth and its effect on natural resources, Marx and Engels engaged thoroughly with Malthusian doctrines, pointing out their hypocritical basis in the furthering of the dominance of rich over poor by "naturalizing" the social causes of poverty and starvation (Marx & Engels, 1971). Marx and Engels argued that there is no overarching law of human population growth per se, and instead insisted that the dynamics of population were specific to different modes of production. Under capitalism, there was an increasing tendency to produce a "reserve army" of unemployed workers that served to keep wages down, but as Polyani showed in his analysis of the English poor laws, there was nothing "natural" about how this excess of unemployed paupers was produced or treated (Polyani, 2001). Neither did Marx or Engels rule out the possibility that at some point human population itself might need to be controlled or limited. But as Engels suggested in a letter to Karl Kautsky, it was precisely a communist society that could best address such problems.

> There is, of course, the abstract possibility that the number of people will become so great that limits will have to be set to their increase. But if at some stage communist society finds itself obliged to regulate the production of human beings, just as it has already come to regulate the production of things, it will be precisely this society, and this society alone, which can carry this out without difficulty (Marx & Engels, 1992: 56).

Because Daly refused to imagine any kind of alternative outside of the capitalist economic system he proscribed the political imaginary of ecological economics to what the capitalist status quo would concede to ecologists through the pressures of lobbying and public debate. This resulted in a political framework which was prone to conciliation and the watering down of its demands in the hopes of getting whatever crumbs the global elite might be willing to throw at it. But far more damaging to the original critique of ecological economics was a development of the theory of "natural capital" which while claiming to provide a framework to appropriately value nature, resulted in returning ecological economics to the fold of neoclassical economics.

THE HEGEMONY OF "NATURAL CAPITAL"

The term "natural capital" was coined by the economist E.F. Schumacher in his

1973 bestseller *Small is Beautiful: Economics as if People Mattered* and became a central component of the discipline of ecological economics by the early 1990s (Burkett, 2006). Schumacher argued that the key problem with humanity's relationship with nature is that we have failed "to distinguish between income and capital where this distinction matters most." (Schumacher, 1973: 14). He suggested that far from having solved the "problem of production," we are unsustainably living off of "capital items" produced by nature and thereby running down the possibilities for continued human existence on this planet. Schumacher writes:

> ...one of the most fateful errors of our age is the belief that the problem of production has been solved. The solution, I suggested, is mainly due to our inability to recognize that the modern industrial system, with all its intellectual sophistication, consumes the very basis on which it has been erected. To use the language of the economist, it lives on irreplaceable capital which it cheerfully treats as income (Schumacher, 1973: 20).

Although Schumacher was the first to coin the term "natural capital" other ecological economists had been grappling with the concept of how to preserve renewable resources and our shared environment in the context of the increasingly obvious ecological crisis of the 1960s and 70s. One of the most influential of these thinkers was the biologist Garrett Hardin wrote his famous essay "The Tragedy of the Commons" for the journal *Science* in 1968. This essay has since been anthologized in more than 100 books, and has become one of the most widely cited essays in the discipline of ecological economics. Hardin argued that the fundamental causes of ecological degradation, pollution and resource depletion came from free access to the "commons" – non-privatized spaces accessible to all. Although he didn't provide any historical or empirical evidence in support of his position, Hardin started from the common sense assumptions of classical political economy and claimed that, because the commons were not economically valued as private property, individuals would use up the freely available natural resources or "ecological services" provided by the commons for their own private gain, with disastrous ecological results. Hardin's outlook provided a crucial rationale for valuing ecological processes as "natural capital."

Like the other ecological economists of his generation, Hardin developed his argument by borrowing from classical political economy. Deriving his argument from the Malthusian proto-marginalist economist William Forster Lloyd's (1795-1852) *Two Lectures on the Checks to Population*, Hardin used Forster's example of a commons on which all members of the community were able to graze their animals (Lloyd, 1833). Taking as his starting point – like all classical economists – that human beings are rational self-interested agents seeking to maximize their own personal wealth and power, Hardin argued that on such a commons, each herdsman would invariably seek to maximize his herd size. Everything would be fine as long as the herd's numbers were below the carrying capacity of the land. However, once carrying capacity was surpassed, "the inherent logic of the commons remorselessly generates tragedy" (Hardin, 1968, 137). With the commons at capacity, each herdsman as a "rational being" seeking to maximize his interests will consider the positive and negative utility in adding an additional animal to his herd. Using a game theory approach, Hardin suggested that adding to the herd will produce a positive utility which will accumulate only to the herdsman (who, Hardin assumes, is free from any customs, traditions or institutions that might regulate his behaviour), while the negative utility (the ecological consequences of overgrazing) will be distributed evenly amongst all herdsmen. Given that all actors are trying to maximize their self interest, each herdsman is compelled "to increase his herd without limit – in a world that is limited. Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons. Freedom in a commons brings ruin to all." (Hardin, 1968: 138)[15]

Hardin extended his analogy to other "commons" such as the oceans which are being overfished and over polluted. Because it is more rational to pollute than to pay for the costs of containment and purification, "we are locked into a system of 'fouling our own nest,' so long as we behave only as independent, rational, free enterprisers" (Hardin, 1968: 139). Rather than question the logic of the free market or constrain its operations through non-market cultural traditions or state policies, Hardin argues that this problem can best be resolved by fully acceding to the logic of the market and commodifying the commons. Hardin saw the extension of private property rights as an ecological safeguard to over-exploitation of natural resources even while recognizing the inequality of market institutions. Indeed, he wrote that:

> an alternative to the commons need not be perfectly just to be preferable. With real estate and other material goods, the alternative we have chosen is the institution of private property coupled with legal inheritance…. we put up with it because we are not convinced, at the moment, that anyone has invented a better system. The alternative to the commons is too horrifying to contemplate. Injustice is preferable to total ruin (Hardin, 145).

In Hardin's vision, capitalism can save the biosphere. Insofar as there is an ecological problem, it is that we have been insufficiently attentive to extending markets to take into account the costs of the depletion of natural resources, the production of toxic wastes, and the enclosure of the global commons. As a result, Hardin's perspective has become one of the central frameworks in developing the notion of "natural capital" that is now hegemonic in ecological economics. As Paul Hawken and Amory Lovins, the authors of the influential book *Natural Capitalism* put it:

> Establishing values for natural capital stocks and flows, as rough as they may be, or – as natural capitalism does – behaving as if we were doing so, is a first step toward incorporating the value of ecosystem services into planning, policy, and public behaviour (Hawken et al., 1999:155).

Far from being an approach that tames or limits capitalism's control over the biosphere, this approach attempts to incorporate all living systems into the capitalist system. The logic being that if all things of value are recognized as such by capitalism, then they will not be recklessly depleted or degraded. Of course, how this squares with capitalism's tendencies towards economic crisis, cutthroat competition, and manipulation of forms of economic valuation is never discussed.

The concept of "natural capital" was confirmed as a core element of ecological economics under the influence of a series of articles by Herman Daly, Robert Costanza, and Salah El Serafy as the discipline became institutionalized in the early 1990s (Burkett, 2009, 101-102). As Burkett notes, the use of the "natural-capital metaphor both reflects and contributes to a strong pressure to re-route ecological economics in neoclassical theory" (Burkett, 2009: 113). In practical terms, the application of neoclassical economics to resolving ecological problems was given further support by the development of market-based "cap and trade" and "carbon offset" proposals which were developed by neo-liberal thinkers in the US in the run-up to the signing of the Kyoto agreement in 1997 (Lohmann, 2006: 47-48). Because capitalists will only save the environment if it is profitable for them, ecological economists essentially ended up in the position of supporting the privatization of the global commons in the hopes that corporations will conserve natural resources in order to be able to continue profiting from them. As Chichilnidky and Heal argued:

> We have to "securitize" (sell shares in the return from) "natural capital" and environmental goods and services, and enrol market forces in their conservation. This means assigning to corporations – possibly by public-private corporate partnerships – the obligation to manage and conserve natural capital in exchange for the right to the benefits from selling the services provided (Chichilnidky & Heal, 1998: 629).

The fundamental problem with the concept of "natural capital" is that it naturalizes capital, which is – as Marx took pains to elaborate – a social relation between people specific to a particular historical epoch, and not an everlasting and reified thing. But the mainstream of ecological economics cannot imagine a world before or after capitalism. According to Robert Costanza and Herman Daly's influential framework, everything is one form of capital or another. They consider ecosystems to be "renewable natural capital," fossil fuels and mineral deposits to be "nonrenewable natural capital," factories, buildings and tools to be "manufactured capital," and human beings to be "human capital." They even consider sunlight to be "natural capital" (Costanza & Daly, 1992: 38)! It is clear that if limited to such a framework, ecological economics can never oppose capitalism per se. Ecological economics has become trapped in a form of thinking in which "the definite social relation between men themselves… assumes… the fantastic form of a relation between things" (Marx, 1990:165). This "commodity fetishism" which seeks to value nature in capitalistic terms occurs because its proponents are unable to look beyond the immediate appearances of the capital-labor dynamic.

> The degree to which some economists are misled by the fetishism attached to the world of commodities, or by the objective appearance of the social characteristics of labor, is shown, among other things, by the dull and tedious dispute over the part played by nature in the formation of exchange value. Since exchange-value is a definite social manner of expressing the labor bestowed on the thing, it can have no more natural content that has, for example, the rate of exchange (Marx, 1990: 176).

Because ecological economics fails to have a "systemic, social-relational conception of capital" it is unable to distinguish between "sustainable development and sustainable capitalism." (Burkett, 2009: 111). The thermodynamic analysis of Georgescu-Roegen offers a powerful critique of conventional economics, but it cannot complete that critique. For that, we need to not only examine biophysical processes but engage with the historically specific social relations of production of a given social formation.

The result of Daly and Georgescu-Roegen's failure to think outside of the box of capitalist social relations when it came to implementing their "minimal biophysical program" or conception of the "stationary state" constrained the political imaginary of ecological economics and foreclosed a potentially generative collaboration with the Marxian critique of capitalist political economy. If the market-based system was an immutable given, and if Malthusian political economy instead of a Marxian critique of political economy was the only acceptable starting point for the development of ecological economics, then it is no surprise that the paradigm of "natural capital" became so dominant in ecological economics. This paradigm makes few demands on the capitalist state, operates entirely within the boundaries of a capitalist political economy, and if successfully practiced will lead to the ever-increasing subsumption of nature into the capitalist system. Consequently, whatever the original intentions of Georgescu-Roegen and Daly, ecological economics has reemerged on the terrain of neoclassical economics and shows few signs of departing from it. However, that does not mean that the thermodynamic analysis advanced by economists such as Georgescu-Roegen and Daly, or natural scientists like Lotka or Odum does not need to be taken seriously. However, for such an approach to be of any real value in either understanding or changing the world it needs to be grounded in a critique of capitalist political economy – something that we will attempt in Chapter 2.

CHAPTER 2 - SOCIAL METABOLISM, DIMINISHING RETURNS, AND THE METABOLIC RIFT

In our first chapter we discussed the inherent challenge that the laws of thermodynamics pose to any living system. All life requires low entropy inputs of energy and matter as well as adequate "sinks" within which to expel the waste produced through metabolism. The human relationship with nature is no exception to this rule, and for the vast majority of the lifetime of our species, humanity maintained a relatively low population which appropriated little in the way of energy and matter from the biosphere, and consequently released little waste or pollution into the environment. The Neolithic Revolution led to a fundamental change in the human metabolism with nature as human beings began to consciously breed and harvest plant and animal species in order to increase the flow of solar energy they could appropriate. Although the transformations wrought by this "Promethean Revolution" were profound, for the next 10,000 or so years humans continued to live within the basic constraints of this expanded flow of solar energy. It was less than 300 years ago that another epoch making transformation occurred, as fossil fuels – which had been widely used for some several hundred years previously as a substitute for declining wood supplies in both England and China – began to be used to power industrial machinery and inaugurated a rapid and far ranging process of industrial and social transformation in 19th century western Europe. The widespread consumption of fossil fuels fundamentally transformed the human metabolism with nature, and saw the rise to global dominance of a dynamic and entirely new form of economic system – capitalism. This new type of economic system had developed several hundred years previously in agrarian form in the English countryside, and its economic logic was soon applied to the new system of industrial manufacture (Brenner, 1995a, 1995b; Wood, 2002; Zmolek, 2010). The combination of capitalist social relations with energy rich fossil fuels produced the most dynamic and expansive economic system humanity has ever experienced.

The hitherto unknown conversion of heat into motion – the energetic basis for the Industrial Revolution – led to the discovery of the laws of thermodynamics as inventors and scientists sought to perfect the steam engine and thereby increase the effectiveness of the primary source of motive power for this new era. The consolidation and rapid expansion of capitalism across the world as it evolved from its agrarian roots in 16th century England was predicated on the ready availability of fossil fuels, and a fundamentally new paradigm based upon unprecedentedly rapid and apparently unending economic growth undermined the classical political economy that had originally theorized the rise of agrarian capitalism in the English context (McNally, 1988). In his history of the development of ecological economics, Juan Martinez-Alier showed that there were a wide range of thinkers – from Serhii Podolinksy, Josef Popper-Lynkeus, Alfred Lotka, Patrick Geddes and Ferdinand Soddy – stretching back to the 1880s who attempted to understand this transformation in energetic terms (Martinez-Alier, 1987). However, these disparate economic thinkers – marginalized by both neoclassical and Marxist orthodoxies – did not produce any kind of coherent theoretical current, and in fact were only rediscovered as the prehistory of the discipline of ecological economics in the wake of a revival of interest in the role of energy following the writings of Georgescu-Roegen and the energy crises of the 1970s (Martinez-Alier, 1987).

As we argued in Chapter 1, ecological economics originally critiqued neoclassical and Marxian economics for not recognizing the fundamental thermodynamic transformation which had occurred as humanity moved from reliance upon a relatively weak and dispersed flow of solar energy to the highly concentrated and energy rich stocks of fossil fuel which became the basis for industrial societies from the 19th century on. As spectacular as the transformation made possible by this access to fossil fuels was, Georgescu-Roegen argued that an economic system based on stocks of fossil fuel energy was no less constrained by the laws of thermodynamics and that the economic paradigms of neoclassical economics and Marxism did not adequately capture the inherently limited nature of industrialism. And yet, at the same time, ecological economists had little to say about the specifically capitalist nature of this development, and nor did the notion of class struggle, or the potential for envisioning the creation of a non-capitalist society enter their analysis. Rather than use Georgescu-Roegen's thermodynamic insights to examine the historical specificity and the economic laws of motion of the capitalist system which developed in the course of the industrial revolution, ecological economists sought to use classical political economy's theorization of the "limits of growth" of agrarian capitalism to critique industrial capitalism and 20th century neoclassical economics. Neoclassical economics considered such a critique irrelevant because it failed to account for the incredible dynamism of capitalist technology and the seeming ability for capitalism to overcome all the ecological limits that it has faced so far. Ultimately, because classical political economy naturalized market relations and the notion of *homo oeconomicus*, ecological economics reemerged on the terrain of neoclassical economics thanks to its focus on "natural capital" and its refusal to consider a solution to the growing ecological crisis by extra-economic means.

The question then arises as to whether it is possible to develop a methodological approach capable of synthesizing the thermodynamic insights of ecological economics with the historical materialist method of Marxism? Certainly, such an approach is promising as it would not only "emphasize the antecedent material-productive conditions of society, and how they served to delimit human possibilities and freedom" but link this approach with the "necessary relation of these material conditions to natural history, that is, to a materialist conception of nature" (Foster, 2000: 19). This kind of analysis would not only pay close attention to the underlying thermodynamic constraints of energy stocks and flows, but could identify how the appropriation of these resources has changed under historically specific modes of production. Such an approach could also open up an analysis of how class conflicts shape the form of a society's metabolism with nature while also examining the possibilities of the supersession of a given mode of production and the development of an alternative metabolic relationship with nature. Outside of the Marxist tradition, there are not a lot of candidates for an approach which blends historical analysis, the defining impact of class struggle, and a close attention to the human relationship to nature. Ecological economics has largely eschewed class analysis, offers little in the way of method to understanding history and the dynamics of social change, and has carefully avoided engaging with ideological frameworks which point to possibilities lying beyond the capitalist system. For its part, neoclassical economics studiously avoids an examination of historical context, ignores class conflict over the economic surplus of society, and considers any discussion of “ecological limits” to be irrelevant.

Nonetheless, an attempt to bridge Marxism and thermodynamics may at first glance seem implausible. In the 20th century – and certainly with some reason – Marxism, especially in its “actually existing” socialist forms, seemed to be yet another authoritarian “Promethean” ideology seeking to maximize industrial economic growth with little concern for ecological dynamics. Many critics of Marxism – and indeed many Marxists themselves – dismissed Marxism as having little to offer in the way of ecological insights, (sources needed). And while it is true that 20th century Marxism has certainly had an ecological blind spot which it has shared with neoclassical economics, what has come to be known as “Marxism” should not be confused with what Marx and Engels actually wrote.[16]

Although most 20th-century Marxists paid little attention to ecological problems, Marx's method and his concept of the relationship between humanity and nature was grounded in a metabolic approach of great relevance to contemporary concerns with energy. This chapter will argue that an attempt to develop an understanding of the relationship between the thermodynamics of capitalist production and the various energy transitions that capitalism has undergone, can be best undertaken by developing Marx’s notion of the metabolism between humanity and nature and linking this approach to an analysis of the dynamics of class struggle under capitalism. This is not to say that Marx’s ecological insights are sufficient for addressing the particular energetic context of the capitalist society that we now inhabit. However, what is so crucial about Marx’s perspective on the societal metabolism between humanity and nature is that he recognizes the historically specific way in which various class societies alter this metabolism, while also developing a theory of capitalist crisis in which low entropy raw materials play a crucial role, while also describing in great detail the way in which class struggles structured by the economic “laws of motion of capitalism” affect this process. This starting point, which remained largely un-explored until the beginnings of the 21st-century when a group of Marxist thinkers including John Bellamy Foster, Paul Burkett, Richard York, and Brett Clark began to re-popularize Marx’s notion of the metabolic rift,[17] offers the potential of grounding the thermodynamic insights posed by ecological economists such as Nicholas Georgescu-Roegen and Herman Daly in a new political basis – one which aims at the transformation of capitalist social relations.

MARX'S CONCEPT OF THE METABOLISM BETWEEN HUMANITY AND NATURE

Let us begin with Marx's concept of the metabolism between human beings and nature, a framework which has led John Bellamy Foster to make a strong case for the argument that Marx's materialism was "deeply, and indeed systematically, ecological" (Foster, 2000: ix). Marx became familiar with the notion of metabolism through his reading of the scientific works of various German agricultural chemists such as Justus von Liebig, as well as by examining the contributions of early pioneers of classical thermodynamics such as Julius Robert Mayer (Foster, 2000: 155-160). Metabolism is a Greek word meaning change or transformation, and in its modern context it was first used by German physiologists in the early 19th century to describe material exchanges within the human body, primarily those relating to respiration (Fischer-Kowalski, 2002). The concept was further advanced by Mayer – one of the founders of the science of classical thermodynamics – who suggested that metabolism could be explained through the principles of the conservation and exchange of energy. There are clear correlations between the metabolic processes of lifeforms at a micro level, and the broader dynamics between nature and human society.

> To sustain the processes of life, a typical cell carries out thousands of biochemical reactions each second. The sum of all biological reactions constitute metabolism. What is the purpose of these reactions – of metabolism? Metabolic reactions convert raw materials, obtained from the environment, into the building blocks of proteins and other compounds unique to organisms. Living things must maintain themselves, replacing lost materials with new ones; they also grow and reproduce, to more activities requiring that continued formation of macromolecules. (Purves et al, 1992, p. 113, quoted in Ayres)

Marx first became familiar with the concept of metabolism in the 1850s, when he came across the work of the famous German agrarian chemist Justus von Liebig, and he first began using the term in the economic writings that were eventually published as the *Grundrisse*. The concept was central to Marx's analysis in *Capital* and he used it to describe what he saw as the fundamental relationship underpinning human existence – the dynamic relationship between human labor and nature. As Marx stressed, in its most basic and fundamental form:

> Labor is, first of all, a process between man and nature, the process by which man, through his own actions, mediates, regulates and controls metabolism between himself and nature. He confronts the materials of nature as a force of nature. He sets in motion the natural forces which belong to his own body, his arms, legs, head and hands, in order to appropriate materials of nature in a form adapted to his own needs. Through this movement he acts

> upon external nature and changes it, and in this way he simultaneously changes his own nature (Marx, 1990: 283).

The central attention given by Marx to the metabolic process in *Capital* reflect the ontological importance of the labor/nature relation as a starting point for Marx's analysis. Although he did not use the term metabolism in his earlier writings, the same focus on the dynamic interrelationship between labor and nature is seen throughout Marx's economic work. In the *1844 Economic and Philosophical Manuscripts*, Marx argued that it is the "conscious life activity" of labor which defines humanity's "species-being" and distinguishes humans from other animals (Marx, 1992: 328-329). Marx understood humanity as deeply linked to nature, stating that "nature is man's *inorganic body*, that is to say nature in so far as it is not the human body. Man lives from nature, i.e. nature is his *body*, and he must maintain a continuing dialogue with it if he is not to die" (Marx, 1992: 328). This dialogue came in the form of humanity's continuous labor, which in interacting with nature, transforms nature and ultimately "reproduces the whole of nature" and allows man to "contemplate himself in a world he himself has created" (Marx, 1992: 329)[18]

Marx accorded a central position to energy considerations in his understanding of labor power, which he treated as a metabolic-energetic process. As Burkett and Foster argue, Marx described labor power as being "above all else, the material of nature transposed into a human organism" – or, in an alternate translation of the same German phrase, "energy transferred to a human organism by means of nourishing matter." (Foster & Burkett 2004: 9) Burkett and Foster show how, in drawing on the work of the German energy physiologist Ludimar Hermann and the English physical chemist Sir William Robert Grove, Marx analyzed the energy inputs to human labor required to reproduce various types and intensities of human labor according to thermodynamic principles. As a result, "Marx's analysis of the value of labor power clearly incorporates the conservation of energy as well as the inevitability of matter-energy dissipation" (Foster & Burkett 2004: 9). Marx did not use the terms "entropy" and "thermodynamics" because "these terms were only then being introduced into physics and thus were not used widely even within the scientific community when Marx wrote Capital."(Foster & Burkett 2004: 9).

In *The German Ideology*, Marx and Engels insisted that the starting point of their materialist conception of history required an examination of the way in which a human society produced and reproduced its existence by means of "the physical organization of these individuals and their consequent relation to the rest of nature" (Marx & Engels, 1998: 37). As they noted, their "manner of approach is not devoid of premises" but instead "starts out from the real premises and does not abandon them for a moment. Its premises are men, not in any fantastic isolation and fixity, but in their actual, empirically perceptible process of development under definite conditions" (Marx & Engels, 1998: 43). As Marx repeatedly stressed, human beings were inescapably a part of nature, and in no matter what stage of historical or economic development humanity is found in, the 'definite conditions of production' always involved some kind of a metabolic relationship with nature.

> The labour-process, resolved as above into its simple elementary factors, is human action with a view to the production of use-values, appropriation of natural substances to human requirements; it is the necessary condition for effecting exchange of matter between man and nature; it is the everlasting nature-imposed condition of human existence, and therefore is independent of every social phase of that existence, or rather, is common to every such phase. (Marx, 1990: 290-291)

While *Capital* is most often read as a work which explains the inner workings of the capitalist economic system and particularly, the way in which surplus value is extracted by capitalists from workers, Marx also discussed the metabolic regime that capitalism imposed upon nature, and the way in which capitalism was responsible for the fundamental ecological crisis of his time – the depletion of soil nutrients in agriculture. As Foster argued, Marx's entry point to this question came through the work of Justus von Liebig who developed a powerful critique of the way in which British farming methods depleted the essential nutrients in the soil required for plant life (Foster 2009, 144). In 1804, the Swiss scientist Nicholas Theodore de Saussure, was the first to assert that plants require carbon and oxygen from the atmosphere and nitrogen, potassium, phosphorus as well as magnesium and calcium from the soil, thereby opening up a field of study aimed at increasing plant yields through the application of chemistry to agriculture (Skaggs, 1994: 2). Building on the contributions of de Saussure as well as other agrarian chemists such as Humphrey Davy and J. B. Boussingault, Liebig attained international renown with his book *Organic Chemistry and its Application to Agriculture and Physiology (1842)*. In his discussion of plant nutrition and English agriculture, Liebig pointed out that the disjuncture between where agricultural produce received nutrients (the English countryside), and where these consumed nutrients ended up (in the form of excrement dumped from London down the Thames River) produced a "rift" between town and country. The minerals contained within the plants were being eaten and excreted by city dwellers, and because human waste was not being returned to the soil, the leaching away of essential nutrients was exhausting the soil and leading to decreasing crop yields.

This process was closely tied to the development of agrarian capitalism in England which had led to a dynamic and export focused agricultural sector as well to the concentration of population in large urban centres. Because its agriculture was closely tied to market imperatives, when faced with falling prices, British producers tended to introduce technological innovations and produce more at lower costs rather than simply cutting back agricultural production as non-capitalist producers tended to do (Brenner). The introduction of capitalist farming in England initiated a series of "agricultural revolutions" that changed the relationship of rural people to the land. As the historian F.M.L. Thompson suggested, the first such "revolution" led to the enclosure of land, increased intensity of cultivation, and an orientation to the market to determine what should be produced. Thompson argued that for the capitalist farmer this revolution required that he "manage the resources of his farm in an orderly, confident, rational, and efficient manner in order to reap the rewards of larger yields, better stock, and greater income per acre farmed" (Thompson, 1968: 63). The other aspect of this style of farming is that it operated as a "closed circuit" in which crops were grown in rotation and in which the manure of grazing animals replenished soils depleted through the production of grain.

While this capitalist approach to agriculture forcibly dispossessed tens of thousands of peasants and rural cottagers, it did prove to be tremendously productive in terms of its physical output. From 1650 to 1750 rising population growth in England was matched by a decline in agricultural prices. However, by the late 1780s grain prices in England began to increase, culminating in extremely high prices during the Napoleonic wars. As prices increased, English farmers brought more lower-quality land into production, land which was incapable of producing as much grain as that produced on best quality land. These dynamics led to Parliamentary debates on the lifting of the "corn laws" – tariffs which protected English grain from being undersold by cheaper imported grain – and it was in the context of rising investments in farming on poorer quality land that classical political economists such as West, Malthus and Ricardo developed both their arguments concerning the inevitability of "diminishing returns" to agriculture and their theories of rent (Cannan, 1892: 62).

In the wake of declining yields and rising prices during the Napoleonic wars, a "second agricultural revolution" took place which put an end to the more ecologically sound farming techniques but also drastically increased agricultural output (Thompson, 1968: 64). Dependent upon the import of animal feeds and fertilizers, this was the kind of farming that Liebig was so critical of – in large part because England was appropriating the natural fertility of other countries in order to improve its own agriculture. One of the key components of this process was the use of oilseed cakes which were derived from the industrial processes used to crush linseed and rape seed into oil. The cakes were then fed to livestock, who produced manure that was considered to be especially fertile. The crops that produced the oilseed cakes were damaging to the soil in which they were produced, and were largely grown outside of Britain. As "British cattle and sheep steadily munched their way through more and more tons of oil cakes, and as steadily dropped their enriched dung on British fields, so they inexorably impoverished the soils of the chief suppliers of the seeds" in Prussia, Russia, India and Egypt (Thompson, 1968: 67).

In the search for new forms of fertilizer, English farmers turned to the importation of bones from across Europe. Napoleonic battlefields were dug up so that the nutrients contained within the bones of deceased soldiers could be acquired and spread across English fields. As the supply of bone meal declined, the naval fleets of England, France and the United States laid claim yet another source of nutrients for the soil – far-flung rocky atolls across the world where large quantities of phosphates and nitrates had been accumulated by tens of thousands of years of bird droppings (Skaggs, 1994). Liebig denounced the hunt for these "natural" fertilizing agents as a form of predation that ruined foreign soil for the sake of and unsustainable and profit driven by British agriculture.

> Great Britain... deprives all countries of the conditions of their fertility. It has raked up the battlefields of Leipsic, Waterloo and the Crimea; it has consumed the bones of many generations accumulated in the catacombs of Sicily; and now annually destroys the food for a future generation of three millions and a half of people. Like a vampire it hangs on the breast of Europe, and even the world, sucking its lifeblood without any real necessity or permanent gain for itself. (Liebig quoted in Foster 2009, 145)

As Foster points out, Marx was especially interested in Liebig's description of the way in which British high farming "robbed the soil" and produced an increasing rift between the nutrients exchanged between town and country. In *Capital*, Marx noted that "to have developed from the point of view of natural science the negative, i.e. destructive side of modern agriculture, is one of Liebig's immortal merits" (Marx, 1990: 638). As Marx wrote to Frederick Engels in 1866, in discussing his work on differential rent for *Capital,* the German agricultural chemists "Liebig and Schonbein, …are more important in this matter than all the economists put together" (Marx, 1979: 205). Marx was fascinated by Liebig's analysis of the role of capitalist agriculture in the depletion of the soil, and particularly in terms of the growing tension between town and country – a question which had preoccupied both he and Engels in their writings in *The German Ideology*. Marx appreciatively quoted Liebig's perspective on the effects of large-scale agricultural capitalism in *Capital*.

> Large landed property reduces the agricultural population to an ever decreasing minimum and confronts him with an ever-growing industrial population crammed together in large towns; in this way it produces conditions that provoke an irreparable rift in the interdependent process of social metabolism, a metabolism prescribed by the natural laws of life itself. The result of this is a squandering of the vitality of the soil, which is carried by trade far beyond the bounds of a single country (Liebig 1842, quoted in Marx 1981).

Influenced by Liebig's conception of the ecological rift between town and country, Marx argued that the domination of capitalist forms of agriculture would ultimately ruin the fertility of the soil. The historical dynamic of capitalism and its "conscious, technological application of science" transforms and "completes the disintegration" of the earlier stages of agricultural production. As a result of the processes of primitive accumulation" which drives peasants off the land, the population is increasingly centralized in large urban settings where it "achieve[s] an ever-growing preponderance" (Marx, 1990: 637). While on the one hand, this process of urbanization and proletarianization lays the groundwork for potentially revolutionary transformations of the capitalist system,

> On the other hand, it disturbs the metabolic interaction between man and the earth, i.e. it prevents the return to the soil of its constituent elements consumed by man in the form of food and clothing; hence it hinders the operation of the eternal natural condition for the lasting fertility of the soil. Thus it destroys at the same time the physical health of the urban worker, and the intellectual life of the rural worker (Marx, 1990: 637).

Because agrarian capitalists are fundamentally interested in making profits, not in preserving or improving soil fertility, Marx argued that capitalism was locked into an inescapable spiral of ecological degradation. Since short-term gains can be made in running down the fertility of the soil, capitalists have no incentive to leave the land they farm in better conditions than they when they found it, especially in the last few years of their leases when they are anxious to recover the costs of the improvements they made on the land. While capitalist farmers may be encouraged to improve their lands by making long term capital investments in the land that will improve productivity, there is also counter tendency that encourages them to allow these longer-term investments to fall into disrepair due to the fear of changing market conditions wiping out the value of fixed capital investments (Perelman, M. 1975: 701). These barriers are not eternal or "natural" but rather stem from the nature of capitalism itself. As Marx put it

> a really rational agriculture is confronted everywhere with insurmountable barriers stemming from private property.… the whole spirit of capitalist production, which is directed toward the immediate gain of money – [is] in contradiction to agriculture, which has to minister to the entire range of permanent necessities of life required by the chain of successive generations (Marx Capital, Volume 3: 617).

Ultimately, the more that capitalism produced agricultural surpluses from the land, the more that it imposed a future limit to overall soil fertility.

> Moreover, all progress in capitalist agriculture is a progress in the art, not only of robbing the worker, but of robbing the soil; all progress in increasing the fertility of the soil for a given time is a progress towards ruining the more long-lasting sources of that fertility. The more a country proceeds from large-scale industry as the background of its development, as in the case of the United States, the more rapid is this process of destruction. Capitalist production, therefore, only develops the techniques and the degree of combination of the social process of production by simultaneously undermining the original sources of all wealth – the soil and the worker (Marx, 1990: 638).

Marx's insight about the connection of large-scale industry to the destruction of soil fertility was particularly appropriate given the changes that were occurring in English agriculture during his lifetime. Under the pressure of capitalist imperatives, English farming was increasingly taking on the characteristics of industrial production. The English agricultural system that Liebig was so vehement in critiquing was the precursor to the modern forms of industrial farming that are so prevalent today. As F.M.L. Thompson pointed out, between 1830 and 1880 the tonnage of animal feed increased by a factor of 10 and the tonnage of fertilizers increased by a factor of 27. By the end of this period, about half of the farmland and half of total farm output in Britain was using industrial resources largely shipped in from outside Britain, leading to a situation in which "farmers regarded their activities as a business; a business that required them to purchase raw materials in the cheapest market, process them in their factories, and sell the final products in the dearest market, just like any cotton lord" (Thompson, 1968: 71).[19]

Outputs of agricultural products have steadily increased under capitalist production since Marx's time, but there is increasing evidence to suggest that, much as Marx predicted, this success has only been achieved at the cost of further ruining the longer-term possibilities of agricultural production. Capitalist agriculture in our era has been compared to the "mining of the topsoil" (find source), where what could be and should be a natural resource capable of restoring itself, is rapidly depleted in the search for quick profits. Today it is estimated that in the US alone, over two million acres of farmland are lost every year as a result of the practice of unsustainable agriculture that produces erosion, soil salinization, and flooding or soil saturation (McMichael, 2007: 178). Even the once fertile Great Plains are losing their capacity for renewal as grain production typically destroys two bushels of topsoil for every bushel of grain produced (source). By the 1960s most temperate grasslands in the world had been brought into production and the only way to stave off declining yields was through a massive increase of energy inputs into agriculture in the form of artificial fertilizers, pesticides, and further industrialization of agriculture. Capitalist agriculture became farming with fossil fuels and agriculture began for the first time to absorb more energy than it produced. On average, every calorie of processed food produced in the United States requires 10 calories of energy to farm, process, and distribute it (Manning).

MARX ON RAW MATERIALS

Although it is often overlooked, there is another way in which Marx's ecological thinking points to the tendency towards ecological and social crisis under capitalism. In a recent discussion of the centrality of "commodity frontiers" to the world historical evolution of capitalism, Jason Moore has drawn attention to the continuing relevance of Marx's 'theory of underproduction' in accounting for "the present socio-ecological impasse" (Moore, 2010). In a little remarked upon chapter entitled "The Effect of Price Fluctuations" in Volume 3 of *Capital*, Marx elaborated a framework for understanding the way in which changes in the availability of raw materials produce variations in the profitability of capital. Marx recognized that "raw materials are one of the principal components of constant capital" adding that "even in industries which consume no actual raw materials, these enter the picture as auxiliary materials or components of machinery, etc., and their price fluctuations thus accordingly influence the rate of profit" (Marx, 1984: 106). Marx also recognized that raw materials varied based on their quality, and that this quality helped to determine the rate of profit by changing the ratio of constant to variable capital. He summed up the impact of high quality raw material as follows:

> Good material produces less waste. Less raw materials are then needed to absorb the same quantity of labor. Furthermore, the resistance to be overcome by the working machine is also less. Assuming wages remain the same, this causes a reduction in surplus labor. This also substantially affects the reproduction and accumulation of capital, which depend more on the productivity than on the amount of labor employed… (Marx, 1984: 83).

In the language of ecological economics, Marx is simply talking about the importance of the use values of high-quality, low entropy raw materials and the threat to profit rates if industrial capitalism can't maintain ready access to a high-quality supply of low entropy resources. Marx framed this dynamic as a "general law," indicating that "with other conditions being equal, the rate of profit is inversely proportional to the value of the raw materials" (Marx, 1984: 111). It is important to remember that in Marx's conception, the "value" of commodities – including raw materials, which by definition have been extracted from nature with the use of labor – is directly proportional to the amount of labor and fixed capital required to produce them. Food or fibre grown on fertile soils, coal drawn from rich seams, or trees harvested from old-growth forests all require less labor and less capital goods to produce, and are thus less costly in value terms to capitalists than lower quality materials drawn from less plentiful environments which require much greater labour and capital inputs. Moore has argued that it has precisely been capital's historical ability to appropriate large amounts of cheap or undercapitalized raw materials that has been so vital to the rapid growth and the dynamism of the capitalist system. Central to this dynamic has been the availability of cheap food to reduce the costs of labor, and cheap energy to power the machinery so central to industrial capitalism (Moore, 2010: 395-398). As Moore notes:

> What capital wants, above all, is to invest a little and to gain a lot: a firm wants minimal capitalization to secure its maximal competitive position. Historically, the secret of capitalism's success has been to maintain strict limits on the extent of capitalized nature. Capital's first preference is to appropriate nature, rather than to produce it through the circuit of capital (Moore, 2010: 401).

But despite capital's desires for cheap raw materials, the availability of these resources is, as Marx put it, limited by nature's own metabolic processes.

> It is, in the nature of things that vegetable and animal substances whose growth and production are subject to certain organic laws and bound up with definite natural time periods, cannot be suddenly augmented in the same degree as, for instance, machines

> and other fixed capital, or coal, ore, etc., whose reproduction can, provided the natural conditions do not change, be rapidly accomplished in an industrially developed country (Marx, 1984: 118).

This dynamic then leads to the "inevitable" problem that in a "developed system of capitalist production," the constant capital represented in machinery "should considerably outstrip the portion consisting of organic raw materials" (Marx, 1984: 118). As a result, there occurs a squeeze on the available raw materials, making their prices rise, increasing their production and the distance from which they are shipped, and also leading to the search for substitutes and the recycling of waste. For Marx, capitalism faces a constant threat of the relative underproduction of the cheap raw materials essential for profitable industrial production.[20] More generally, Marx's critique of the tendencies of capitalist farming can also be seen to be at work in his theory of underproduction, as the "organic laws" of agriculture can be outpaced by the rapid expansion of fossil fuelled industry. It is worth noting that in the quotation above, Marx compared organic inputs from plants and animals to the inorganic minerals that industrial capitalism requires. He suggests that the inorganic minerals required as inputs can be rapidly augmented in a way that organic materials which are dependent upon growing seasons cannot be. But note that he specifies that this is only possible as long as "the natural conditions do not change." But of course, the "natural conditions" of production for inorganic materials do inevitably change as soon as they begin to be extracted. The richer and more easy to access mineral resources tend to be depleted first, and then greater investments of fixed capital and variable capital are required to maintain inputs of lesser quality. Marx sums up his argument as follows:

> The greater the development of capitalist production, and, consequently, the greater the means of suddenly and permanently increasing that portion of constant capital consisting of machinery, etc., and the more rapid the accumulation (particularly in times of prosperity), so much greater the relative over-production of machinery and other fixed capital, so much more frequent the relative under-production of vegetable and animal raw materials, and so much more pronounced the previously described rise of their prices and the attendant reaction. And so much more frequent are the convulsions caused as they are by the violent price fluctuations of one of the main elements in the process of reproduction (Marx, 1984: 118-119).

In Marx's time, organic raw materials were an indispensable part of the industrial system. The textile industry was the leading sector of the Industrial Revolution, and all clothes came from organic fibers, be they wool, cotton or flax. Today, while organic raw materials are still essential for capitalist production – especially in the form of commodified inputs for food production – the use of fossil fuels such as oil to produce synthetic fibres has alleviated much of the strain from agriculture in this regard. But as has often been remarked, oil and other petrochemicals are too valuable a resource to burned up as fuel (Perelmen, 1980: 393). As oil supplies become depleted, a substitute will need to be found both as a fuel, and as a raw material – a problem which may lead to a returned dependence on the organic raw materials so crucial for early capitalism. In Volume 3 of *Capital*, Marx followed up his analysis on the underproduction of raw materials with a lengthy description of the impacts of the cotton shortage of 1861-65 (triggered by the impact of the US Civil War) on the English industrial cotton manufacturers. Due to ill health, Marx was unable to prepare the manuscript of Volume 3 for publication, and the remainder of this section – like other parts of the volume – consists of notes and extracts from primary sources that he was later intending to work up into a polished and completed text. Consequently, while Marx does provide us with a jumping off point to further interrogate the role of raw materials in capitalist production, he did not flesh out his analysis of this dynamic to anywhere near the same degree that he analyzed the labor process or the process of primitive accumulation in the first volume of *Capital*.

But the fact remains that by means of an attentive reading of Marx's actual writings on the metabolism between humanity and nature, a very different picture begins to emerge of the sensitivity of the founders of Marxism to the concerns raised by ecological economics. As Burkett and Foster argue, Marx and Engels "relied on an open-system metabolic-energetic model which adheres to the main thermodynamic strictures of ecological economics, but which also (unlike ecological economics) roots the economy's violation of solar and other environmental sustainability conditions in the class relations of production" (Foster & Burkett 2004: 9). As we will see in Chapter 4, Marx also paid close attention to the way in which the machine technology of industrial capitalism was central to the winning of the ongoing class struggle between labor and capital. If as Lukacs argued, orthodoxy in Marxism relates primarily to method (Lukacs, 1971: 1-26), than the centrality of Marx's social analysis of metabolism, his identification of a "metabolic rift" between town and country, and his analysis of the crises of underproduction of raw materials for industrial capitalism all point to a possible framework to develop a convergence of a Marxist ecology and ecological economics that is consistent with the practices of historical materialism. Such a perspective in shares much common ground with the thermodynamic analysis of production of ecological economists such as Georgescu-Roegen.

> What Marx and Engels generated in their historical-dialectical materialism was a theory of the capitalist labor, production and accumulation process that was not only consistent with the main conclusions of thermodynamics originating in their time, but also extraordinarily open to ecological laws.... in other words, classical Marxism, contrary to widespread myth, has an extraordinary affinity for what has become known as "ecological economics… "(Foster & Burkett 2004: 28)

Unfortunately however, the conceptual tools that Marx developed were largely ignored by 20th century Marxist theorists, and thus have been rarely applied in efforts of concrete social analysis. If the ecological Marxism elaborated by Foster and Burkett does share some "extraordinary affinities" with ecological economics, Marx's ecological perspective still needs to be carefully teased out – especially because of Marx's own failure to develop it more explicitly. In particular, the line of thinking that we have pursued here raises some intriguing questions about the elaboration of Marx's thought on ecological and agricultural questions. We have seen in Chapter 1 how ecological economists made a wholesale return to classical political economy and its notion of a "stationary state" in an effort to develop a better grounding for their concerns over economic growth. This raises the interesting question of how Marx's unequivocal certainty of the disastrous long-term effects of capitalist agriculture compares to the theory of "diminishing returns" in agriculture that underlaid Smith and Mill's notion of the inevitability of the stationary state. Similarly, Mill's efforts in applying the law of diminishing returns to extractive industries seems to foreshadow contemporary concerns by ecological thinkers over the "peaking" and decline of key energy resources required for the continuation of industrial capitalism. How does Marx's theory of the under production of raw materials compare to Mill's framework? More broadly speaking, if the conceptual framework of the law of diminishing returns in fact expresses the inexorable influence of the second law of thermodynamics, how should a Marxist framework relate to it?

THE LAW OF DIMINISHING RETURNS

Before Marx, classical political economy also had a theory of crisis focusing on the agricultural sector. The "law of diminishing returns" was developed simultaneously by 18th century English and French political economists as a means of expressing the fact that perpetual agricultural improvement was impossible. Because of the fact that agricultural production was the source of food and industrial inputs, the law of diminishing returns led to a deeply pessimistic theory of economic development and the assumption that society would eventually enter a "stationary state." The economic historian Joseph Schumpeter attributes the first formulation of the law of diminishing returns to the English political economist James Steuart (1712-1780), who argued that "as population increases, poorer and poorer soils have to be taken into cultivation and, applied to these progressively poorer soils, equal amounts of productive effort produce progressively smaller harvests" (Schumpeter, 1981: 259). The French Physiocrat A.R.J. Turgot (1727-1781) came to similar conclusions, arguing that as capital and labor are:

> …applied to a given piece of land, the quantities of products that result from each application will first successively increase up to a certain point at which the ratio between increment of product and increment of capital will reach a maximum. Beyond this point, however, further application of equal quantities of capital will be attended by progressively smaller increases in product, and the sequence of these decreasing increases will in the end converge toward zero (Turgot quoted in Schumpeter, 1981: 260).

The most famous exposition of the concept of diminishing returns in classical political economy arises from David Ricardo's theory of rent. Although Ricardo neither invented the concept of diminishing returns nor was the first to claim that diminishing returns produced rent[21] his name has been linked with the notion of differential rent due to the influence of his *Principles of Political Economy* in the 19th century debates on the corn laws.

Ricardo argued that rent – "that compensation, which is paid to the owner of the land for the use of its original and indestructible powers" – historically arose due to population growth and was determined by the differing qualities of the land (Ricardo, 1817). In a socio-economic context where there was a small population and a limitlessly fertile soil, there would be no rent – for the same reason prices cannot be affixed to items of "boundless quantity" like air and water (Ricardo 1817).[22] Similarly, if all land was of the exact same quality and was equally accessible to markets, Ricardo argued that rent would not exist. However, as population grew, increasing requirements for subsistence would lead to more land being brought into production.

At first, the most fertile and conveniently situated land would be used, and this land would garner no rent. After this land (land of type I) had been brought into production, population pressures would lead to land of the next best quality (land of type II) being developed. Because land of type II was of lesser quality and by definition would produce a smaller product with the same amount of labor and capital invested in it as the first, land owners would impose rent on the higher-quality land of type I. This would happen as a means of equalizing the profit rates between capitalists farming lands of differential fertility, since "rent is always the difference between the produce obtained by the employment of two equal quantities of capital and labor" (Ricardo, 1817: 3). Because Ricardo, like most other classical political economists, assumed that since population would continue to rise to the extent that the means of subsistence allowed, new lands of even lower quality (land of type III) would come into production to feed the rising population. Once these lands were in production rents would increase on land of type I, and rent would be applied to land of type II. Because it was of the worst quality, land of type III would not pay rent – until even worse quality land – land of type IV – came into cultivation.

As a result of his theory of rent, Ricardo held that the prices of raw produce raised from the land would steadily increase because of the increasing costs of labor required to produce grain on lands of constantly decreasing fertility. And as production increased on lands of lower fertility, rents would rise and the landlords – an unproductive class that made no contribution to production – would increasingly benefit. Inevitably, food prices would go up because of the higher labor costs involved in raising grain on lands of lower quality, and higher food prices meant higher costs of subsistence, and thus higher wages (Ricardo, 1817: 5). The combined effect of rising rents and wages would squeeze capitalist profits, and would result in the arrival of the kind of "stationary state" state that Adam Smith warned of. Ricardo did suggest that there were a few counter-tendencies that could slow this process down. Chief among them was the lifting of tariffs that blocked importation of cheaper agricultural products from elsewhere, and the use of technological improvements which could allow for increased grain production without higher costs of labor. This explains Ricardo's opposition to the "corn laws" which put tariffs on imported corn and thereby kept wages and rent high.

While Ricardo's theory would seem to offer some ecological insight into the problems of economic growth, the overall focus of his analysis failed to address the important questions which Turgot raised in his analysis of diminishing returns. Schumpeter notes that there were in fact two different conceptions of the law of diminishing returns, what the followers of Ricardo were to term the "intensive" and the "extensive" margin (Schumpeter, 1981: 259) – and what Marx, in his analysis would term "Differential Rent I" and "Differential Rent II" (Marx, 1984: 649-684). Although the concept was familiar enough to farmers stretching back to the dawn of agriculture, Schumpeter praised Turgot with having discovered the intensive margin – the dynamic in which successive applications of labor and capital to a particular parcel of land would tend to first produce increasing returns, and then eventually produce decreasing returns per extra unit of labor or capital applied. The extensive margin referred to Ricardo's conception that as population grew, increasingly inferior soils that were previously at the margin of cultivation would need to be farmed and that these lands would bring decreasing returns as compared to more fertile land originally cultivated (this perspective is also reflected in the quote from Steuart above). Ricardo had very little to say about the intensive margin of diminishing returns, referring only offhandedly to the way in which an application of manure or machinery could improve the produce of the soil (Ricardo 1817). Unlike the way in which James Anderson conceived of differential fertility, Ricardo never considered that farmers had the capacity to improve or degrade the level of soil fertility, and thereby affect the levels of rent in the productivity of the land. This disconnect between intensive and extensive margins was continued by most other economic theorists that built off of Ricardo's theory of diminishing returns, and tended to preclude the development of an ecological framing of the issue of diminishing returns.

As we discussed in Chapter 1, most classical political economists thought that the amount of produce ultimately available from the land was inherently limited and prone to diminishing returns. Because all raw materials for industry and all food for the population came from the same area of land, it was evident that a growing population – itself seem as an important part of a progressive or expanding economy – would require steadily increased cultivation of land. The British historian E.A. Wrigley argued that the concept of diminishing returns held in "organic" environments, as increased agricultural production produces a "negative feedback system" which "set[s] in train changes that make further growth additionally difficult because of the operation of declining marginal returns in production from the land." As he put it:

> Each step taken made the next a little more painful to take. In parts of an organic economy, because of the effect of specialization of

> function, increasing returns are obtainable and positive feedback existed, but, since each round of expansion necessarily increased pressure on the land by raising demand for industrial raw materials, as well as food, in the system as a whole negative feedback tended to prevail. In a mineral-based energy economy, in contrast, freed from dependence on the land for raw materials, positive feedback could exist over a large and growing sector of economic activity (Wrigley 29-31).

Of all the classical political economists, John Stuart Mill provided perhaps the most sophisticated and thorough account of the law of diminishing returns. Like Ricardo, he began his analysis from the standpoint that unlike the other factors of production – labor and capital – land cannot be increased indefinitely. There is only so much land in the world and its quality varies according to the nature of the soil and the surrounding climate. The assumption that because agrarian capitalism in England had registered steadily increasing gains in productivity, no final limits to the increasing productivity of the land would ever be reached was "not only an error, but the most serious one, to be found in the whole field of political economy. The question is more important and fundamental than any other…" Mill went on to add that, "were the law to be different, nearly all the phenomena of the production and distribution of wealth would be other than they are" (Mill, 1987: 176-177).

Unlike Ricardo, Mill also discussed the intensive margin of diminishing returns. In discussing the practice of agriculture, Mill compared "the limitation to production from the properties of the soil" to "a highly elastic and extensible band, which is hardly ever so violently stretched that it could not possibly be stretched anymore, yet the pressure of which is felt long before the final limit is reached, and felt more severely the nearer that limit is approached" (Mill, 1987: 176-177). The "law of production from the land" is that regardless of "any given state of agricultural skill and knowledge, by increasing the labor, the projects is not increased in an equal degree" (Mill, 1987: 177).

However, Mill was also quick to acknowledge that the law of diminishing returns is counterbalanced by the growth of the productive forces and the "progress of civilization". These improvements fall into two broad categories. "Some enable the land to yield a greater absolute produce, without an equivalent increase of labor; others have not the power of increasing the produce, but have that of diminishing the labor and expense by which it is obtained." (Mill, 1987: 183). Among these varying factors, Mill included advances such as crop rotation, the introduction of new vegetable and animal species, the application of manure and guano, tile drainage, and machinery that spares manual labor on the farm. The development of new roads, railways and canals cheapen the cost of transport, while improvements in metallurgy lower the costs of agricultural implements, railroads, wagons and carts, ships, and even buildings – all of which lower the cost of production of food and postpone the onset of the law of diminishing returns (Mill, 1987: 183-185).

However, in the last resort, because all the materials of manufacture are "drawn from the land… the general law of production from the land, the law of diminishing return, must in the last resort be applicable to manufacturing as well as to agricultural history" (Mill, 1987: 185). Recognizing the various mechanical improvements, labour-saving devices, benefits of economies of scale, and the contributions made by an increasingly educated workforce, Mill concluded that like agriculture, manufacturing is reliant upon extractive industries, which themselves are subject to the law of diminishing returns.

> As a mine does not reproduce the coal or ore or taken from it, not only are all mines at last exhausted, but even when they as yet show no signs of exhaustion, they must be worked at a continually increasing cost; shafts must be some deeper, galleries driven farther, greater power applied to keep them clear of water; the produce must be lifted from a greater depth, or conveyed a greater distance (Mill, 1987: 1888).

Mill is here using the exact same framework of analysis used by the geologists and environmentalists warning of the approaching peak of global oil production (Hubbert, 1949; and Campbell, 1998). And yet Mill is also quick to point out that there are countervailing factors mitigating the tendency towards mineral exhaustion. As he points out:

> Mining operations are more susceptible of mechanical improvements than agriculture: the first great application of the steam engine was to mining; and there are unlimited possibilities of improvement in the chemical processes by which the metals are extracted. There is another contingency, of no infrequent occurrence, which avails to counterbalance the progress of all existing mines towards exhaustion: this is, the discovery of new ones, equal or superior in richness. (Mill, 1987: 188)

Mill's conception of the "law of diminishing returns" thus reflects a tendency affecting all forms of production. The resemblance of Mill's argument to the perspective of ecological economists and peak oil advocates is uncanny. The phenomenon of diminishing returns may be postponed, but not infinitely. The determining factor in whether the law can be avoided has to do with the level of technological advance and development within a society.

THE MARXIAN CRITIQUE OF DIMINISHING RETURNS

Marx's engagement with the law of diminishing returns largely came through his critique of Ricardo's theory of rent in the process of developing his own theory of ground rent. Marx criticized Ricardo's rent theory on two major lines. The first concerned the way in which Ricardo naturalized the capitalist mode of production in his theory of ground rent, and the second challenged Ricardo's assumptions that a rising population always leads to the use of lands of decreasing fertility.

One of the primary grounds for Marx's critique of classical political economy was due to its habit of naturalizing capitalism and projecting it backwards in history as a social form inherent to human nature. This is what Ricardo did with his theory of rent, in assuming that the origin of ground rent in England had followed the same processes which were then occurring in Britain's colonial holdings in North America as a result of the quality of land and the size of the population.[23] In contrast, Marx argued that rent was the product of definite social relations, and a means by which landed interests were able to claim from capitalists a portion of the surplus value produced by the labourers involved in agricultural labor. As he put it, "rent is a product of society and not of the soil" (Quoted in Perelman, M., 1973: 165).

Marx argued that there was no such thing as a universal or transhistorical theory of rent, but rather that different forms of rent were specific to different kinds of class societies, and that forms of rent could go through changes even within these class societies.[24] The way in which rent was organized as the appropriation of a portion of the societal surplus in feudal society, was quite different from the way in which rent was appropriated under capitalism, and rent was by no means an immutable fact of social life. Marx's insistence of the historical specificity of economic categories is well summed up in his critique of Proudhon:

> [Proudhon] has not perceived that *economic categories* are the only *abstract expressions* of these actual relations and only remain true while these relations exist. He therefore falls into the error of the bourgeois economists who regard these economic categories as eternal and not as historic laws which are only laws for a particular historical development, the development determined by the productive forces (Marx, *Poverty of Philosophy*, quoted in Meek, 143).

This perspective held for other dynamics such as population growth, which played such a central role in Ricardo's analysis of the origins of rent and the law of diminishing returns. As Marx argued in relation to Malthus's theory of population growth – a theory which Ricardo and most other classical political economists subscribed to – the human population that is considered "surplus" under capitalism is not the natural product of human fertility, but is rather an outgrowth of the social relations of a particular stage of capitalist development which through its own workings displaces workers from the countryside and produces a "reserve army of labor" which has the effect of keeping wages down. This process has nothing to do with what Malthus, Ricardo, and other classical economists claimed were everlasting "natural laws" of population. Those so-called "natural laws" were instead "a law of population peculiar to the capitalist mode of production; and in fact every special historic mode of production has its own special laws of population, historically valid within its limits alone. An abstract law of population exists for plants and animals only, and only in so far as man has not interfered with them" (Marx, theories of surplus value, quoted in Meek, population bomb, page 94).

In *Theories of Surplus Value,* Marx commented extensively on Ricardo's theory of rent and unfavourably contrasted it to the work of James Anderson, who had developed a theory of rent prior to Ricardo. The significance of Anderson's analysis is that while he also argued that rent arose as a means of equalizing profit on lands of differential quality, "he stressed not only that the absolute productivity of all types of land could be constantly improved and must be improved with the progress in population, but he went further and asserted that the *differences* in *productivity* of various types of land can be progressively *reduced"* (Marx, theories of surplus value, Chapter 9). Marx appreciated Anderson's work because it provided the basis for a refutation of Malthus's theory of population (even though Malthus, Marx argued, plagiarized Anderson's theory of rent and distorted it in the interests of the landlords). Also of interest was the fact that in as early as 1801, Anderson, decades before Liebig, pointed out that soil fertility was being depleted because of the division between town and country and the consequent failure to return human wastes to the soil (Foster, 2000: 145-146).

Marx's analysis stressed the importance of soil fertility in relationship to the continued output of the land. In contrast, Ricardo and the other classical political economists saw soil fertility as something that was fixed and unchanging, and spoke of the "original and indestructible powers" of the soil (Ricardo, 1817). Marx critiqued Ricardo for being unable to explain a situation in which land was becoming increasingly infertile as result of harmful agrarian practices, or a situation in which less fertile ground was being improved through methods of farming which restored soil fertility. Consequently, Ricardo's theory of rent could express in some general terms the limitations faced by an agrarian society which had to draw all of its resources from the land, but it said precious little about the ecological factors that determined soil fertility. Because of their insufficient knowledge of soil science, Marx argued that neither Ricardo nor Malthus were able to develop an adequate theory of rent. [Find quote. Somewhere in Vol 1…]

Marx critiqued Ricardo's assumption that land would constantly decrease in its fertility, and pointed out that in historical terms Ricardo's theory had been refuted by economic data in the first half of the 19th century (Marx & Engels, 1982: 258). In *Capital* Vol. 3, Marx devoted over 200 pages to elaborating and improving upon Ricardo's theory of differential rent, and examined through the use of a series of tables the different ways in which rates of profit, rent and output changed in conditions of increasing, decreasing, and stable soil fertility. As a result of the way in which capitalist farmers could improve the fertility of their own lands through capital investments or through the importation of raw materials such as seed cakes, bone meal or guano, Marx did not argue as Ricardo did that diminishing returns would lead to economic stagnation and eventually a stationary state. Marx did agree that the social relationship between landed property and agricultural capital led to the enriching of the former at the expense of the latter, but as Engels pointed out, the expansion of capitalism with its "transoceanic steamships and railways of North and South America and India enabled some very singular tracts of land to compete in European grain markets" (Marx, 1984: 726). This competition had the effect of removing a large portion of European lands from cultivation, and as Engels happily reported, were leading to the ruin of big and small landlords in Europe. So, through the extension of the world market to regions without landed property and the bringing in to production of fertile lands requiring little capital investment and artificial fertilizer, capital could overcome the stranglehold of the landed aristocracy which Ricardo thought would dominate over capital (Marx, 1984: 726).

Unfortunately, Marx never completed Chapter 43 of Vol. 3 of *Capital* where he examined differential rents where production costs increased while working with the poorest quality land in production. But in the following chapter entitled "Differential rent also on the worst cultivated soil" Marx summarized his position on how the declining productivity in the land affected capital. Here he pointed out that "natural elements entering as agents into production, and which cost nothing" do not "enter as components of capital, but as a free gift of nature to capital… which, however, appears as a productiveness of capital, as all other productivity under the capitalist mode of production" (Marx, 1984: 745). But, if this natural power, which does not enter into the determination of price, is diminished, or is not able to supply an increased demand, and thus must be assisted or replaced with human labor power, then "a relatively larger investment of capital is thus required in order to secure the same output. All other circumstances remaining the same, a rise in the price of production takes place" (Marx, 1984: 745). This formulation is quite similar to Marx's analysis of raw materials and the importance of undercapitalized nature to capitalist profitability. Soil fertility, while it may have started off as "naturally determined" ceased to be a pure product of nature as increasing amounts of human labor were applied to the land. To the extent to which "natural fertility" declined and had to be replaced with inputs and "improvements" to the land provided by capital, costs would rise, and profits would decline as the "free gifts of nature" diminished.

Having said this, Marx was of course aware of the international aspect of the metabolic rift in which English lands were being improved at the expense of agricultural land elsewhere. The metabolic rift and the depletion of the soil were problems caused by the way in which land was treated as a form of fixed capital for the purposes of surplus extraction. To treat the soil in this way was irresponsible and had historically led to the despoliation and desertification of once fertile lands.

> Improvements to the land need reproduction and upkeep; they last only for a time; and this they have in common with all other improvements used to transform matter into means of production. If land as capital were eternal, some lands would present a very different appearance from what they do today, and we should see the Roman Campagna, Sicily, Palestine, in all the splendour of their former prosperity (1973, Poverty of Philosophy, pp. 164-65).

One of the few places where Marx expressly commented on the law of diminishing returns was in a footnote to the famous passage in *Capital* where he argued that "all progress in capitalist agriculture is a progress in the art… of robbing the soil," (Marx, 1990: 638). In this footnote Marx critiqued Liebig for not only mistaking John Stuart Mill as the originator of the law of diminishing returns, but for suggesting that the law "is the universal law of agricultural industry" (Marx, 1990: 639). As far as Marx was concerned, a number of different agricultural systems could be devised to regulate the metabolism between humanity and nature. "The moral of history" was that

> that the capitalist system works against a rational agriculture, or that a rational agriculture is incompatible with the capitalist system (although the latter promotes technical improvements in agriculture), and needs either the hand of the small farmer living by his own labor or the control of associated producers (Marx 1984: 121).

A rational, socialist agriculture could, Marx argued, mend the metabolic rift between town and country and thus (following Anderson) build up soil fertility while also increasing agricultural output. At the same time, there were other forms of "rational agriculture" that were not based on the pillage of the soil, and here Marx pointed to the way in which small-scale farming outside of the sway of the world market could be ecologically benign. The contributions that Liebig and other agrarian chemists made to improving yields suggested to Marx that the depredations of capitalist agriculture could be overcome, and that large scale scientific agriculture could drastically increase outputs if the metabolic rift could be resolved by a shift towards a socialist form of production that overcame the division between town and country. So for Marx, it did not make sense to postulate a universal law of diminishing returns that applied across different historical contexts. Marx would have likely been sympathetic to the perspective that Engels' put forward in his 1844 *Outlines of a Critique of Political Economy* – a text which introduced Marx to the field of political economy (Comninel, 2000b). In response to Malthus's doctrine of population, Engels argued that while

> the extent of land is limited…. The labor power to be employed on this land-surface increases with population. Even if we assume that the increase in yield due to increase in labor does not always rise in proportion to the labor, there still remains a third element which, admittedly, never means anything to the economist – science – whose progress is unlimited and at least as rapid as that of population. What progress does the agriculture of this century owe to chemistry alone – indeed, to two men alone, Sir Humphrey Davy and Justus Liebig! (Marx & Engels, 1971: 25-26).

In another reply to Malthus's argument that diminishing returns accounted for the problem of increased poverty and would ultimately condemn the human race to a life of misery, Engels argued that the tremendous technological advances opened up by capitalism would serve to revolutionize agriculture by means of the application of science in the same way in which capitalism had revolutionized industry:

> We start from the premise that the same forces which have created modern bourgeois society – the steam engine, modern machinery, mass colonization, railways, steamships, world trade – and which are now already, through the permanent trade crises, working towards its ruin and ultimate destruction – the same means of production and exchange will also suffice to reverse the relation in a short time, and to raise the productive power of each individual so much that he can produce enough for the consumption of two, three, four, five or six individuals. Then town industry as it is today will be able to spare people enough to give agriculture quite other forces than it has had up to now; science also will then at last be applied in agriculture on a large scale and with the same consistency as an industry; the exploitation of the inexhaustible regions fertilized by nature herself in southeastern Europe and Western America will be carried out on an enormous scale hitherto quite unknown (Marx & Engels, 1971: 86).

Such technological and social progress should lead to the production of vast agricultural surpluses which would more than provide for the caloric needs of humanity. But Engels also showed foresight in allowing for the possibility that even the vast new territories being opened up by the extension of the capitalist system might themselves provide insufficient. “If all these regions have been plowed up and after that a shortage sets in, then will be the time to say *caveant consules* [to sound the alarm]” (Marx & Engels, 1987: 135). And if despite all of the contributions of capitalist technology and science,

> …Malthus were altogether right, it would still be necessary to carry out this (socialist) reorganization immediately, since only this reorganization, only the enlightenment of the masses which it can bring with it, can make possible that moral restraint upon the instinct for reproduction which Malthus himself put forward as the easiest and most effective countermeasure against this overpopulation" (Marx & Engels, 1971: 120-121)

Something that is often overlooked in readings of the work of Marx and Engels is the extent to which their analysis of capitalism occurred in the infancy of this newly emerging economic system. When Marx and Engels wrote the *Manifesto of the Communist Party* for example, capitalist social relations were dominant only in a relatively small part of Western Europe and the Americas. The fact that “the bourgeoisie cannot exist without constantly revolutionizing the instruments of production” and that the scientific and technological revolutions unleashed by this new capitalist system created productive forces “more massive and more colossal” than those belonging to “all preceding generations together,” led Marx and Engels to argue that the main form of crisis produced by capitalism in their epoch was one of overproduction (Marx & Engels, 1848). In an era of international commerce, massive capitalist expansion centred on the vast and largely “under-developed” agricultural and resource rich territories in North America, Southern

Africa, Australia, and Eastern Europe, the major problem limiting capitalist growth was not diminishing returns to the productivity of the relatively small amounts of land under intensive cultivation in England and Western Europe, but rather the internal barriers to the capitalist mode of production itself. It was these epidemics of capitalist overproduction that pushed society "back into a state of momentary barbarism," and these crises perversely appeared "as if a famine, a universal war of devastation, had cut off the supply of every means of subsistence; industry and commerce seem to be destroyed." The problem in this era was not the lack of resources and finished use-values, but rather the fact that relative to its ability to absorb it, capitalist society had produced "too much civilization, too much means of subsistence, too much industry, too much commerce" (Marx & Engels, 1848).

LENIN ON DIMINISHING RETURNS

In the context of early 20th century debates on the agrarian question, later Marxist thinkers such as Vladimir Lenin were quick to dismiss the concept of diminishing returns as a trans-historical abstraction, but they also lacked Marx's ecological insights. While Lenin was severe in his critique of the concept, Mill would have surely agreed with Lenin that the law of diminishing returns "does not apply at all to cases in which technique is progressing and methods of production are changing; it has only an extremely relative and restricted application to cases in which technique remains unchanged"[25] (Lenin, 1975: 110). More to the point was Lenin's argument that instead of the law of diminishing returns placing limitations on the forces of production, it was capitalist relations of production which denied cheap food to the working class.

> It has become more difficult for the workers to obtain [food] because capitalist development has inflated ground rent and the price of land, has concentrated agriculture in the hands of large and small capitalists, and, to a still larger extent, has concentrated machinery, implements, and money, without which successful production is impossible. To explain the aggravation of the worker's condition by the argument that Nature is reducing her gifts can mean only that one has become a bourgeois apologist (Lenin, 1975: 111).

In *The Agrarian Question and the "Critics of Marx"* Lenin responded to Bulgakov's critique of Karl Kautsky's *Agrarian Question*, and showed the contributions which Marxism made to analyzing both the underlying social dynamics which regulate the functioning of a given society, even if he failed to examine the physical laws which shape the way in which a particular society appropriates energy from the biosphere. On the one hand, even Lenin had to admit that on a very basic level, the law of diminishing returns exists. For if the law didn't exist, then "it would be possible to carry on the agriculture of the whole globe upon one *dessiatine* of land" (Bulgakov, quoted in Lenin, 1975: 109). On the other hand, Lenin quite rightly pointed out that while undeniable, this argument has been deployed by Malthusians as an "empty abstraction" which ignores the level of technological development and the state of the productive forces (not to mention the social relationships between classes and the metabolism between humanity and nature) that condition production process. Mill, for example, shared the Malthusian notions of other classical political economists and argued that the law of diminishing returns provided a justification for social inequality. As he wrote "The niggardliness [sic] of nature, not the injustice of society, is the cost of the penalty attached to overpopulation. An unjust distribution of wealth does not even aggravate the evil, but, at most, causes it to be somewhat earlier felt" (Mill, 1848: 191). While quite rightly pointing out the political basis for this openly ideological rationalization of capitalist inequality, Lenin made the inverse mistake in his polemic by never considering the ecological component of the question, the fact that there are indeed limits to how much food energy a given soil can produce sustainably. Instead Lenin would seem to suggest that not only is the level of technological development "the most important thing" it is the only thing that needs to be considered.

Interestingly, Lenin does not once use Marx's concept of metabolism in his polemic with Bulgakov despite the fact that much of Lenin's polemic is focused on Bulgakov's interpretation of Marx's analysis of capitalist agriculture in *Capital*. Presumably Lenin's reluctance in this regard stemmed from the fact that as both he and Bulgakov agreed, at the turn of the 20th century capitalist agriculture was making great increases in production and that advances in agronomy had made it possible to replace the nutrients lost through the metabolic rift between town and country (Lenin, 1975: 151-152). In a similar vein, Kautsky, in his 1899 exposition of the Marxist position on agriculture, *The Agrarian Question,* never used or elaborated upon Marx's concept of metabolic relationship between labor and nature. [26] Kautsky discussed the contributions of Liebig, and stressed the way in which capitalism as an economic system was unable to overcome division between town and country (Kautsky, 1988: 53-54), but he failed to further develop (or even note) Marx's numerous comments on the way in which capitalism ruined the fertility of the soil. At other times, Kautsky even seemed to echo the comments of Ricardo and Malthus, stating that "…the soil is eternal and indestructible, at least from the standpoint of human society" and that "land cannot be destroyed" (Kautsky, 1988: 85, 209).

Perhaps the reason for the reluctance of such orthodox Marxists as Kautsky and Lenin to elaborate on Marx's notion of the metabolic rift stems from the fact that Marx himself did not ever carry out a thorough study of "the agricultural question." The agricultural historian Colin Duncan is particularly critical of Marx's failure to analyze the human metabolism with nature outside of the capitalist context and to examine the fundamentally destabilizing nature of agriculture itself as constant battle against a natural process of ecological succession (Duncan, 1996: 9). In relation to Marx's treatment of the agricultural question in *Capital,* Duncan notes that:

> In relation to the very strong language Marx uses here, his treatment of the question is disproportionately brief. Marx's analysis of the capitalist mode of production tells us a great deal

> about the second of the two "original sources of all wealth" and does so in a highly systematic way. The references to the other "original source" are, by contrast, random, few in number, fleeting, and often unreliable (Duncan, 1996: 189).

Duncan certainly has a point here, and the fragmentary if consistent nature of Marx's writings on the metabolism could have certainly done with with further exposition – especially in his discussion of the various types of differential rent in volume 3 of *Capital*. At the same time, there is more than enough within Marx's account of the metabolic relationship between humanity and nature for Marx's framework to serve as a starting point for the development of an anti-capitalist and socialist ecology. If as Marx argued, the metabolism between humanity and nature "is the everlasting nature-imposed condition of human existence, and therefore is independent of every social phase of that existence, or rather, is common to every such phase" (Marx, 1990: 290) then an examination of the ways in which this social metabolism with nature changes within each different social phase and how biophysical processes are related to class antagonisms specific to these phases is surely required. It can be surmised that further study of the nature of this relationship would reveal distinctive metabolic characteristics in varying modes of production, or even of distinct phases tied to particular energy regimes within capitalism. It is in regards to this question of the distinctive phases of capitalist development that Marx's conception of social metabolism and its relationship to class struggles can be most usefully explored.

CHAPTER 3 - ENERGY AND ECOLOGICAL LIMITS IN PRE-CAPITALIST SOCIETIES

We ended our last chapter by suggesting that varying modes of production had different metabolic relationships with nature and that capitalism itself had undergone a series of changes in its underlying energy regime. This chapter will attempt to conceptualize some of the ways in which the human metabolic relationship with nature has been transformed by the evolution of class society since the emergence of agriculture. It will also extend Marx's argument by suggesting that "the specific economic form in which unpaid surplus labor is pumped out of direct producers" (Marx, 1984: 791) also has a thermodynamic character, and that particular modes of production can be correlated to specific energy regimes which are in turn produced, maintained, or transformed as a result of the economic "laws of motion" of these modes of production. The rest of this chapter will examine historical evidence of the ways in which thermodynamic limits have shaped the pre-capitalist metabolism between humans and nature. We will stop short of discussing the specific social and metabolic relationships that attended the transition from feudalism to capitalism, and the transition from agrarian to industrial capitalism, as these will be the topics of chapters 4 and 5.

The question of how to tease apart the relationship between the social organization of production and humanity's biophysical relationship to nature is a complicated one. It is clear that the underlying characteristics of a given mode of production – the technical and social means by which a human society secures its own reproduction – have a significant bearing on the consumption of energy and materials. For over the course of the past 2 million years of hominid evolution, it has only been in the last 12,000 years or so that groups of humans developed alternatives to the small hunting-gathering societies that had been spread out over the earth's surface in more or less metabolic equilibrium with the biosphere since time immemorial. At around the end of the last Ice Age, in half a dozen different locations, humans began to independently develop class stratified agrarian societies which not only fundamentally changed the human metabolism with nature but launched a process of rapid social evolution which remains with us today.

From within these early agricultural societies, a series of social and technological revolutions gave rise to the first civilizations, civilizations which over time shifted their geographic centres and experienced a succession of historical "ages" – the Bronze Age, the Iron Age, and more recently, what could be termed the steel, fossil fuel, and microprocessor age – which have been generalized across the globe. With each of these transitions, the production and consumption of low entropy energy and materials increased, and the metabolic rift between humanity and nature expanded. Even in the earliest stages of the Neolithic Revolution, many societies exhausted the local fertility of their topsoil, created serious problems of deforestation, and otherwise limited their long-term possibilities of economic development. In our present age, the search for the low entropy energies necessary to fuel the machine technology so central to our economy has seen humanity become a force with effects noticeable in geological terms. To pick but one example, a single engineering project – the Syncrude mine in the Athabasca tar sands – now moves some 30 billion tons of earth each year in its quest to provide the US economy with an alternative to declining sources of conventional oil. This nearly incomprehensible mechanical feat – carried out by over-sized vehicles four stories high – displaces twice the amount of sediment that is currently carried downstream by all the rivers in the world. The capacity of human beings to alter the climate and geology of the world has led to some scientists suggesting that our current geological epoch should be dubbed the Anthropocene – or "the age of man" ("Welcome to the Anthropocene," 2011).

The question of how and why human societies moved from our humble origins as hunter gatherers to a species which appropriates some two thirds of the world's net bio-mass production and releases enough carbon dioxide from the burning of fossil fuels to create potentially catastrophic global climate change is an important one. Some ecological economists have attempted to see the evolution of human society in energetic terms (Martinez-Alier, 1987). Frederick Soddy, a Nobel prize-winning chemist and one of the forefathers of ecological economics, argued that in understanding the development of human society, the physical laws of thermodynamics had to be given priority in explanatory terms.

> The laws expressing the relations between energy and matter are not solely of importance in pure science, they necessarily come first in order, in the fundamental sense described, in the whole record of human existence, and they control, in the last resort, the rise and fall of political systems, the freedom or bondage of nations, the movements of commerce and industry, the origins of wealth and poverty, and the general physical welfare of the race (Soddy, 1922: 10-11).

Soddy was undoubtably correct that both the increased access to energy in our contemporary society and the need for more of it is a central factor in accounting for both why a feat of engineering like Syncrude's is possible and why it is being carried out now. However, Soddy's framework is incapable of explaining why contemporary Canadian society would, for example, choose to produce energy from the tar-sands in the first place and not limit its energy consumption, increase its energy efficiency, or develop alternative forms of energy such as solar or wind power instead. Understanding the policy choices which have led to the development of the tar sands requires an appreciation for a myriad of social factors – including class and regional dynamics within Canada, the relative political weakness of environmental and indigenous sovereignty groups, the influence of the international energy industry, and the US's geopolitical interest in avoiding over-reliance on supplies of Middle Eastern oil among other factors (Stainsby; Nitiforik; Laxer). While it is undoubtable that the access to the world's fossil fuel energy resources made possible by the Industrial Revolution played a decisive role in the emergence of the Anthropocene, a string of other social and technological transformations had to occur before these fossil energies could be tapped and human society set on this trajectory. We are for example confronted with the curious question of why the ancient Greeks who had invented the first steam engines were unable or unwilling to use them as sources of motive power, or why the Romans – with all their military and engineering prowess – contributed so minimally to scientific or technological advancements, or why despite the widespread industrial use of coal in 12th century China, there failed to arise there a self expanding industrial revolution as was the case in 18th century England (Childe, 1971; Braudel, 1984; Pomeranz, 2001).

And while the 6000 years from the emergence of civilization in Mesopotamia to the present might seem like an awfully short time for humanity to undergo the sort of cultural evolution that it has, much of this time has been spent in periods of technological stagnation that lasted millennia. Indeed, as the anthropologist Leslie White argued, it wasn't until it began the use of fossil fuel energy in machine technology became widespread in the early 19th century that European civilization surpassed "in any profound and comprehensive way, the highest levels achieved in the Bronze Age" of some 3000 years earlier (White, 1949: 373). For the major transformations in terms of life expectancy, demographic growth, and human impact on the environment, we are talking about a period of time covering less than two centuries of extremely rapid growth. It seems clear that while there is clearly an energetic basis to the tremendous processes of change unleashed since the Neolithic Revolution and accelerating so rapidly after the Industrial Revolution, we must look at social causes and the relationships determining the "rules of reproduction" for a given society and thereby its metabolic relationship with nature.

It is here that once again we will find rich insights into understanding the ways in which societies grow and evolve by looking to the Marxist tradition and in particular, the Marxist concept of a "mode of production" which is central to the historical materialist theory of history. Ecological economics, in relying so heavily on the concepts of classical political economy, has largely been unable to offer a genuinely historical and social examination of the rise of class society and the consequent changes that have occurred with the human metabolism with nature. Unlike the classical political economists, Marx did not consider capitalism to be a stable and unchanging economic system, but rather to be one particular type of class society, albeit one which was tremendously dynamic and effective in its expansionary tendencies.

Rather than seeing capitalism to be an eternal human condition expressing our intrinsic tendencies to "truck, barter and trade," Marx, due in part to his historical context, was very much aware of capitalism's emergence and the possibilities for its supersession. While Marx devoted most of his intellectual efforts to trying to understand the functioning of the capitalist system, his life's work was not simply about interpreting this system, but rather about throwing his lot in with the social forces that he felt were compelled to transform and supersede capitalism. The thought that an economic class could upend an established social formation and create a new mode of production did not seem strange or impossible to Marx and many other revolutionaries of his time. The generation that immediately preceded them had lived through the French Revolution and the Napoleonic wars, and by the time that Marx reached maturity, capitalism was still very much engaged in transforming the old feudal order which still held sway over much of Europe. As George Comninel reminds us, the Germany that Marx grew up in was not a capitalist society, and when Marx sought political refuge from the German autocracy by taking up residence in London, he stepped "across the bounds of pre-capitalist social experience to confront the character of a qualitatively different universe of capitalist social relations" (Comninel, 2000: 483). For Europeans, the first half of the 19^{th} century was, as Eric Hobsbawm termed it, "the age of revolution" and Marx was both a careful observer and a passionate participant in these revolutionary movements (Hobsbawm, 1996).

In the lead up to the 1848 revolutions which swept across Europe, Marx and Engels noted the revolutionary characteristics of the capitalist class, writing that "wherever it has got the upper hand," the bourgeoisie "has put an end to all feudal, patriarchal, idyllic relations. It has pitilessly torn asunder the motley feudal ties that bound man to his "natural superiors", and has left remaining no other nexus between man and man than naked self-interest, than callous "cash payment" (Marx & Engels, 1848). Capitalism was actively remaking the world in its own image, and even as it did so, the working class that it had called into being threatened to unleash its own revolution – first in the French July Revolution of 1830, and then in the pan-European revolutions of 1848 (Lowy, 2005). Like all other social systems based on class antagonisms, capitalism laid the groundwork for its own transformation as the increase in social wealth that it made possible was constrained by the class relations inherent to it. In the capitalist society they were witnessing, the working class grew in proportion to the growth of capital, and in the *Manifesto of the Communist Party* Marx and Engels wrote that "what the bourgeoisie therefore produces, above all, are its own grave-diggers. Its fall and the victory of the proletariat are equally inevitable" (Marx & Engels, 1848). In his conception of socialist revolution, Marx drew inspiration from the various revolutions of the 19th century which saw a previous mode of production – European feudalism – overthrown through social revolution, and Marx had long been interested in the political struggles of antiquity and the way that transitions in earlier modes of production had taken place (Ste Croix, 1975: 12-15).

Central to Marx's understanding of the process of transition between modes of production was the contradiction between the underlying "material productive forces of society" and the "property relations" of the existing social order. Aware of the tremendous increase in human technology and labor productivity that had taken place since the development of human civilization, Marx argued that the productive power of these forces had been successively increased through varying modes of production. A set of social property relations could be historically progressive and revolutionary in comparison to those that they replaced, but as the productive forces developed, these relations tended to ossify and become "fetters" on the further development of human society and its productive forces (Marx, 1859). It was in these moments of contradiction between the forces and relations of production that Marx argued that an "epoch of social revolution" would emerge, for in cases where real opportunities for the increase of productive capacities existed but were held back by the social relations of the day, there existed a strong incentive for social change given the promise of real returns for the subaltern groups that stood to benefit from such improvements in the productive forces (Cohen, 2002).

Marx argued that capitalism marked the end process of this dynamic of class struggle because it represented the most complete separation and furthest alienation of the direct producers from the means of production (See Wood, 2000). Further expansion of the capitalist system would inevitably provoke a socialist revolution which would thus overcome the 10,000 years of class oppression which began with the demise of the communistic hunting gathering societies in the face of the rise of agriculture and the emergence of private property. The working class – all of those displaced from their own access to the means of production and compelled to labor for capital – was thus a profoundly revolutionary class because it was a class "which no longer counts as a class in society… and is in itself the expression of the dissolution of all classes, nationalities, etc., within present society" (Marx, 1998: 60). As evidenced by the close attention that Marx paid to Lewis Morgan's work on "archaic communist" societies, (Anderson, 2010) Marx saw that there was a parallel between these early communist societies and the socialist future he envisioned. As Engels stressed in quoting Morgan in the closing paragraph of *The Origin of the Family, Private Property and the State*, the communism of the future could be seen as an extension and reassertion of an original communist past:

> democracy and government, brotherhood and society, equality in rights and privileges, and universal education, foreshadow the next higher plane of society to which experience, intelligence and knowledge are steadily tending. It will be a revival, in a higher form, of the liberty, equality and fraternity of the ancient gentes (Morgan, quoted in Engels, 1942: 163).

It would be interesting to see what Marx and Engels would have thought of Marshall Sahlins' research that suggested that hunting-gathering societies were the "original affluent societies" in which all the requirements for subsistence could generally be gathered with the labor of a few hours each day, leaving the majority of time for contemplation and enjoyment of life (Sahlins, 1974). In this kind of society, Marx's description of the future communistic society appears realized: "nobody has one exclusive sphere of activity but each can become accomplished in any branch he wishes, society regulates the general production and thus makes it possible for me to do one thing today and another tomorrow, to hunt in the morning, fish in the afternoon, rear cattle in the evening, criticize after dinner, just as I have a mind, without ever becoming a hunter, fisherman, shepherd or critic" (Marx, 1998: 53).

The correlation between past and future communist societies is also interesting from a thermodynamic perspective. As Sahlins notes, while the hunter-gather metabolism with nature produced a smaller total sum of energy than any other mode of production, from a thermodynamic perspective, it has been the most energy efficient mode of production, and enjoyed per capita energy consumption levels no lower than most traditional agrarian societies (Sahlins, 1974: 5-6). If we accept the argument that the metabolic rift in hunting-gathering societies was consciously minimized, it becomes all the more interesting that in Marx's vision of communism, human society becomes "the perfected unity in essence of man with nature, the true resurrection of nature, the realized naturalism of man and the realized humanism of nature" (Marx 1844). And more explicitly, in *Capital*, Marx specifically notes that freedom requires that

> socialized man, the associated producers, govern the human metabolism with nature in a rational way, bringing it under their own collective control instead of being dominated by it as applying power; accomplishing it with the least expenditure of energy and in conditions most worthy and appropriate with their human nature (Marx 1981 [1865], 957).

Consequently, the communist overcoming of the metabolic rift through the resolution of the division between town and country, and the control of the metabolism of nature to minimize the amount of energy used has interesting parallels with the metabolic relationship of humans and nature in pre-class societies. For, as Marx argued, not only will the communist society of the future revive the "liberty, equality, and fraternity" of archaic communism, but it will also revive a relationship with nature that is not fundamentally based upon a metabolic rift – a relationship which only acquires an institutional status with the development of class society.

Despite the ecological insights that are evident in Marx's accounting of the metabolic transformation undertaken in a communist future based upon the "free association of producers" one of the major blind spots in the Marxian analysis of the transformation between different modes of production has been the role that thermodynamic processes play in such transitions. If the dynamism of a social formation is defined by its capacity to develop new productive forces, what is the relationship between the development of these forces and the appropriation of new forms of energy? To what extent was the development of human civilization and the transition between various forms of tributary societies predicated on the discovery of new sources of energy, and to what extent was the capitalist supersession of feudalism due to the negative feedback produced by ecological dynamics? Can social formations become historically outmoded because of their inability to avert ecological crisis or acquire the necessary stores of low entropy materials? And in the case of such a crisis, can social upheavals open up the way for a further expansion of the productive forces in the face of the ecological breakdown of the old order?

We have seen in Chapter 2 how Marx's analysis of the ecological contradictions specific to capitalism's metabolic rift suggests that both ecological and economic crises may arise through the exploitation of the soil, and we have also noted how Marx outlined the notion of a crisis of underproduction caused by the inability of the production of renewable raw materials to keep up with the ever increasing demands of industrial capitalism. Although few Marxists after Marx considered such overall ecological factors as an explanatory factors which might preclude further room for development of the productive forces of a given social formation, such an approach does seem to have some promising insights for the development of an ecological Marxism – especially given the growing threat of anthropogenic climate change which confronts humanity today, and the near complete failure of advanced capitalist countries to take steps to avert it.

A research program seeking to examine the role energy across different forms of social organization faces serious difficulties because it requires an analysis of the ways in which ecological dynamics have affected very different kinds of economic systems. As Marx himself stressed, comparing modes of production across different eras can be problematic, given that by definition they have such different mechanisms for regulating and organizing the production and consumption of the social surplus. And of course, the greatest error of classical political economists was to assume that the cultural and economic features of the capitalist society they were familiar with prevailed in all previous epochs – a mistake which is still made by many bourgeois economists today. But nonetheless, as Marx reminded us, there are still opportunities for discussing the features of "production in general."

> Whenever we speak, therefore, of production, we always have in mind production at a certain stage of social development, or production by social individuals. Hence, it might seem that in order to speak of production at all, we must either trace the historical process of development through its various phases, or declare at the outset that we are dealing with a certain historical period, as, e.g., with modern capitalistic production which, as a matter of fact, constitutes the subject property of this work. But all stages of production have certain landmarks in common, common purposes. Production in general is an abstraction, but it is a rational abstraction, insofar as it singles out and fixes the common features, thereby saving us repetition (Marx, 1998: 2).

Consequently, examining production from the standpoint of the material flows of low entropy inputs and the high entropy pollution that occurs as a result of production could well offer a potentially useful way of framing production relations in ecological terms. For as Marx argued, all forms of production have in common the fact that they involve the application of various kinds of human labor to natural materials for the purposes of producing use-values to meet human needs. The labor process is "the necessary condition for effecting exchange of matter between man and nature; it is the everlasting nature-imposed condition of human existence, and therefore is independent of every social phase of that existence, or rather, is common to every such phase" (Marx, 1990: 290-291). And yet, at each different phase of this metabolism with nature, the labor process is regulated by the social and technical organization of production, which is itself determined by the social/property relations of a given society.

No matter how production is organized, it must at the very least allow for the production and reproduction of human labour and the forces of production that sustain the human metabolism with nature. Ideally, the human body requires a food input of between 2500 and 3000 calories a day and no mode of production can last for long if it is unable to provide the means to reproduce human labor itself. Of course, most human societies are consistently able produce more than this biophysical minimum, and they do so by using exosomatic tools combined with human knowledge and labour (or "forces of production" in the Marxist idiom) to appropriate low entropy energy and materials from nature. The tools and technologies in different human societies vary widely, but because all forms of production involve at root the application of human labor (mediated through a variety of different technologies) to nature, the conditions of production common to all forms of human metabolism with nature can be expressed in thermodynamic terms. Any analysis of the labor process 'resolved into such simple and elementary factors' is necessarily limited at this level of analysis, and says little of the social relations between classes that ultimately govern a given form of production. Indeed, as Marx noted in a discussion of the general features of the human metabolism with nature, at such a level of abstraction,

> It was, therefore, not necessary to represent our labourer in connexion with other labourers; man and his labour on one side, nature and its materials on the other, sufficed. As the taste of the porridge does not tell you who grew the oats, no more does this simple process tell you of itself what are the social conditions under which it is taking place, whether under the slave-owner's brutal lash, or the anxious eye of the capitalist, whether Cincinnatus carries it on in tilling his modest farm or a savage in killing wild animals with stones (Marx, 1990: 290-291).

And yet, a description of the ways in which thermodynamic processes constrain and shape all forms of the human metabolism of nature can help to illuminate the background against which particular class societies exert distinctive pressures that shape the metabolic relationship in one way or another. Let us begin by summarizing, in the form of a series of theses, some of the key insights that have emerged thus far from our analysis of ecological economics and Marx's conception of the metabolism between labor and nature. These perspectives, we argue, hold true for all forms of "production in general."

THE THERMODYNAMICS OF "PRODUCTION IN GENERAL"

1. The production process does not involve the creation of new energy or matter, but only rearranges existing forms of energy and matter through the human metabolism with nature. As Marx put it, "When man engages in production, he can only proceed as nature does herself, i.e. he can only change the form of the materials" (Marx, 1990: 133). Furthermore, according to the second law of thermodynamics, the production process is inherently entropic – in addition to creating use-values, production and consumption inevitably create pollution and increase the total entropy of the energy and materials involved in the process. As they are produced and consumed, a proportion of these

materials become unavailable for further use – the rubber worn away from tires, the metal lost to rust, the coal reduced to ashes, etc.

2. Because we live in a finite world with fixed stocks of low entropy energy and materials, and because we are only able to appropriate limited (although renewable) flows of energy and matter, there are undeniable limits to economic growth, even if the temporal limits to such growth – given the capacity for technological innovation and the impact that social policies can have on economic dynamics – cannot be accurately predicted.[27] Growth is not only limited by the inputs to the production process but also by the outputs – our biosphere has only a finite capacity to absorb pollution as the problem of global warming reminds us. This does not mean that industrial capitalism is about to collapse, but from a thermodynamic perspective it does suggest that such a system cannot last indefinitely. The ultimate longevity of any economic system ultimately depends on the availability of low entropy energy and materials on the one hand, and the capacity of pollution sinks to absorb waste on the other hand.[28]3. The greater the throughput of energy and matter in humanity's metabolism with nature, the quicker the material basis for this metabolism will be undermined. Alternatively, if humanity's metabolism with nature is entirely based on the appropriation of renewable flows of energy and matter (and is within the bounds of their regeneration) and if the amount of pollution is within the capacity of the biosphere to absorb and dissipate it, than an economic system is capable of indefinite development if not infinite growth. [29]4. The matter and energy consumed in the human metabolism with nature can be divided into two forms: stocks and flows. Stocks are finite supplies of low entropy matter which have been deposited on geological timescales exceeding the lifespan of the human species. Examples of such stocks include fossil fuels such as oil, uranium, natural gas, and coal as well as minerals such as iron ore, gold, phosphorus, etc. On an energetic level, flows include the flux of solar energy that can be converted through photovoltaic panels, as well as wind and water power which can be converted by wind turbines and hydroelectric facilities. Material flows include animal and vegetable biomass which if harvested in sustainable ways, are capable of indefinitely reproducing themselves. Of course, if over harvested, "renewable" resources can cease to be renewable and can be depleted in a similar way to nonrenewable resources.

5. Because stocks represent finite resources they are prone to dispersal and depletion through the production process. The richer and more easily accessible stocks of a given resource are generally the first to be used up because they require less effort to extract. As exploitation of a given resource continues, the costs of production (in both energetic and price terms) tends to increase since by definition lower quality stocks require more effort to extract and refine. New technologies may counter this tendency by leading to the discovery of new and richer deposits, enabling the substitution of a different resource for one which is becoming increasingly scarce, or by allowing for the exploitation of previously untenable deposits, but because any given material resource is finite and unevenly distributed across the world's surface, the "productivity" of a given stock tends to decline over time with its exploitation. In the case of many materials –

including most famously oil – production of the resource follows a bell shaped curve which "peaks" so that the highest rate of consumption of the material occurs at a point when approximately half of the resource has been consumed.

6. Flows of material and energy are relatively static. An example of this is the amount of solar energy which hits the Earth's surface on a given part of the globe. The flow of solar energy cannot be increased or decreased by humans, though its intensity does vary with the position of the earth in relation to the sun, the location on the surface of the earth where it lands, and the ebb and flow of solar flares or sunspots. Examples of flows of material include the amount of biomass created in terrestrial or marine ecosystems. The appropriation of animal and vegetable life from the land is determined by a wide range of factors, but is ultimately delineated by the amount of solar energy received by a specific area of land and the capacity of primary plant producers to photosynthesize this energy. As energy is passed up the food chain from autotrophs to heterotrophs, the second law of thermodynamics predicts the dissipation of about 90% of this energy in the form of waste heat as it moves through each stage of the trophic pyramid. While the production of biomass may be increased or decreased due to a variety of environmental and ecological factors, its growth is not infinite, for it is limited by the physical space on the earth's surface it takes up and by the its ability to turn solar energy into physical structures. Because the production of biomass can't be infinitely increased, as the uppermost level of production is reached, the phenomenon of diminishing returns makes itself felt. [Check Odum for more material.]

7. All forms of metabolism involve the conversion of energy from one form to another, and the human metabolism with nature is no different. The first and original energy converter is the human body itself, which takes in food energy in the form of calories derived from plants and animals and is then able to perform useful work. The number of known energy converters is quite limited and can be listed as follows: human and other animal bodies, the photosynthesis of various plants and bacteria, a variety of different wind and water turbines, sails, the heat engine (including the steam engine and the internal combustion engine), the electric motor, and photovoltaic solar panels. As Debeir et al. put it "clearly, the most frequent energy problem in all human societies is more one of converters than sources: from this standpoint, a history of energy is a history of energy converter systems" (Debeir et al., 1991: 4). Various ways of structuring modes of consumption and production can increase or diminish the efficiency with which this energy is used, but the ability of humans to appropriate energy is determined by the efficiency of the energy converters that are used.

8. The efficiency of energy converters is limited. Interestingly, of all animals, humans have one of the highest conversion rates, as our bodies are able to turn approximately 20% of the calories that we take in into mechanical work. Horses and oxen have a much lower efficiency, and only convert about 10% of the calories they take into usable work (Debeir et al, 1991). Through photosynthesis, plants are able to convert only about one

percent of the solar energy that they receive. Photovoltaic solar panels can convert about six percent of the solar energy they receive. Wind turbines can only convert a theoretical maximum of 60 percent of the wind energy that flows through them. Etc. [expand]

9. Irregardless of its socio-technological level or of their relations of production, if any human society seeks to maximize its appropriation of energy flows or stocks with its existing energy converters, it will inevitably face diminishing marginal returns as it approaches the limit of conversion mandated by the second law of thermodynamics, or in the case of stocks, the point at which more than half of the resource has been consumed. The crucial variable concerns how much of an existing material resource there is, and the capacity of a given society to scour the globe for it. The ability of today's global market and fossil fuelled industrial system to seek out the material resources necessary for social reproduction are orders of magnitude greater than, for example, the capacity of the Roman Empire to ensure the continued flow of slave labor, tribute, and grain from the then known world.

It is worth noting that in the theses proposed above, the law of diminishing returns plays a part in three different dynamics listed above. Firstly, the stores of fixed terrestrial low entropy resources exhibit tend to exhibit diminishing returns once more than 50% of the global resource has been extracted. Secondly, the renewable resources based upon photosynthesis tend to reach upper limits in their production of biomass. Finally, the efficiency of a given energy converter exhibits diminishing returns as it is increased towards its theoretical maximum.

While it is quite true that different kinds of society with different relationships to nature face the outcomes of the law of diminishing returns in different ways, all human metabolic relations with nature are subject to the second law of thermodynamics, and it is this law that produces *the tendency* towards "diminishing returns" across all manner of human social formations. As Georgescu-Roegen pointed out, the laws of thermodynamics govern this process because "…the entropy law is the taproot of economic scarcity. In a world in which [the entropy] law did not operate, the same energy could be used over and over again at any velocity of circulation one pleased and material objects would never wear out" (Georgescu-Roegen, quoted in Mirowski, 1988: 821). Some modes of production, like capitalism, may seem to overcome this tendency by displacing it in time and space through the adaption of new technologies or different energy sources, but they cannot escape its long-term operation. In this regard, Marx's approach was quite prescient in seeing capitalism as an economic system which produced short term fertility at the expense of "ruining the more long-lasting sources of that fertility" (Marx, 1990: 638).

Georgescu-Roegen identified several different "Promethean revolutions" which qualitatively transformed humanity's appropriation of energy sources and which enabled whole new "energy regimes" to be built around specific technologies. And yet, each one of these revolutions (the invention of fire, the Neolithic revolution, and the development of the heat engine) reached particular limits, prescribed by the laws of thermodynamics. The amount of biomass available for burning is limited by the speed at which plants can metabolize sunlight and the physical amount of land available for their growth. The production of food crops or the grazing of animals is similarly limited by the flow of energy. Each time we go up the food chain, and advance a trophic level, the energetic efficiency decreases by a factor of about 10. This is because animals which live off of other animals or plants, are unable to convert energy into work without wasting a significant proportion of that energy as heat. Similarly, the efficiency of heat engines is limited by the laws of thermodynamics. Even the most efficient heat engines can not be run beyond the limit of the Carnot cycle, and in practice heat engines are much less efficient then their theoretical maximum.[Expand.] Great gains in efficiency may be made through experimentation and technical development -- for example, the efficiency of the steam engines invented by Thomas Newcomen which began the Industrial Revolution, were only about 5% efficient, while those today are x% efficient but the point remains that thermodynamic limits place real restrictions on what is possible. In addition to limits on the conversion of energy to useful work or to food products that can be absorbed by human beings, we must also take into account the availability of pollution sinks to absorb the byproducts of the economic process.

The second law of thermodynamics essentially acts as a brake on the exertion of life. This is true at a biological level much as it is at a social level. These laws can be overcome for a period of time through the development of technological means which increase the flow through of energy or matter and thereby allows a higher level of social complexity. However, ultimately these new innovations will themselves face declining returns. Constant ever-expanding growth is impossible. The entropy law – and the associated effects of friction, the inevitable degradation of energy into waste heat, etc. – acts as a constraining factor on human attempts to “do work” on the surrounding environment. Technological innovation and the use of new energies and materials can produce remarkable gains and temporarily hold back the law of diminishing returns, but in a situation where technological innovation and other factors of production are held static or are unable to grow quickly enough, the laws of thermodynamics dictate that a progressive decline in marginal output will occur.

3. THE HISTORICAL TREND OF THE HUMAN METABOLISM WITH NATURE

Despite the inherent pessimism of the above observations of thermodynamic processes, it would appear from casual observation that human evolution – like life itself – has flaunted these rules (Needham, 1942, Schrödinger, 1944?). When viewed over the long term, the history of human kind is one of an ever-increasing expansion in the flow through of matter and energy in production. While there have been long periods of relative stagnation of the productive forces, it is undeniable that taken as a whole, the last 12,000 years of human history have seen a rapid expansion in the rate of the human metabolism with nature. Even without delving into the vital questions of *how* class dynamics and changes in technology have shaped the human metabolism with nature, some general observations can be drawn from the historical evolution of "production in general" which we will again discuss in thesis form.

1. In emerging from its animal origins, the human metabolism with nature was based strictly upon those foods that could be acquired through hunting and foraging and which did not require chemical change in order to be consumed. Most anthropologists and archaeologists argue that material lives of our early ancestors, Homo Erectus began under conditions not dissimilar to those in which chimpanzees and other great apes live today (Knight, 1991).

2. Humans "begin to distinguish themselves from animals as soon as they begin to *produce* their means of subsistence" (Marx & Engels, 1998: 37) and some 2 million years ago our hominid ancestors began using tools which functioned as "exosomatic" organs which replicated and enhanced the capacities of the human body. For the vast majority of our evolutionary history, human-based energy was our only source of motive power, while exosomatic instruments were limited to simple wooden and stone implements.

3. For more than 99% of the last 2 million years of our species' existence we lived in small bands of hunters and gatherers. Anatomically modern humans, despite using very limited supplies of energy and materials, had managed to spread to every major landmass in the world some 40,000 years ago. Until the development of agriculture with the Neolithic Revolution some 12,000 years ago, it is estimated that the total global human population had remained steady at approximately 4 million people for more than 200,000 years. Some 3000 years after the Neolithic Revolution began, population had grown to 5 million people and then began doubling every thousand years until the human population reached 50 million in 1000 BC and grew to 100 million in 500 A.D. (Ponting, 1991: 37). By 200 A.D., the human population had reached 200 million and by the beginning of the Industrial Revolution had reached 610 million (Ponting, 1991: 92).

4. There have been three major "Promethean" revolutions during which energy consumption surged forward and created conditions conducive to massive social change. [30] The first of these came with the "domestication" of fire some 400,000 years ago, the second with the domestication of plants and livestock and the consequent development of agriculture some 12,000 years ago, the third and most recent came with the development of heat engines and the use of fossil fuels some 300 years ago. Each of these transitions saw a qualitatively significant transformation in the human metabolism with nature. In each case, the technological advances that were made were generalized across human societies and produced tremendous quantitative and qualitative social changes.

5. The domestication of fire is associated with the expansion of the human species out of Eastern Africa and across the globe. Fire provided a wide variety of evolutionary advantages, enabling humans to not only improve their hunting methods, their capacity to

consume and store new kinds of food, to extend their climate into colder regions, but also fundamentally reshaped the social dynamics by which people lived. [Need reference to book on fire.]

6. The Neolithic Revolution and the domestication of plants and animals marked another fundamental turning point in human society. At its root, this transformation was about the development of new methods of energy conversion, and saw the development – through generations of human labor involved in domestication – of human co-evolution with a wide variety of plant and animal species. Domesticated plants and animals gained widespread reproduction and spreading of their genes, while human beings won new capacities to convert energy into forms which could be saved up and consumed later. As human societies came in touch with each other they introduced each other to new plant and animal varieties which had been domesticated in different cultures. The development of agriculture – occurring simultaneously in half a dozen different for parts of the globe with the end of the last Ice Age – made possible the emergence of the first great Bronze and Iron Age empires in the fertile alluvial deltas of Mesopotamia, Mesoamerica, China, the Indus Valley, and the Nile – civilizations whose cultural and technological achievements were not surpassed until the beginnings of the 18th century Industrial Revolution.

7. The industrial revolution – often defined as the application of fossil fuel powered machine-based technology to standardized forms of production – emerged in mid 18th century England with the development of large-scale factories predominantly powered by wind and water power. By the early 19th century these factories were increasingly powered by energy rich coal which was burnt in steam engines which for the first time allowed humans to convert heat energy into mechanical motion. The use of steam engines as a universal agent which could provide power not only in industrial production, but could also drive steamships across the sea and locomotives across newly developed rail lines transformed the British economy into a global superpower and laid the basis for the most profound and wide-ranging change in the human metabolism of nature. The Industrial Revolution of the 19th century heralded an exponential increase in the throughput of energy and matter and the interweaving of capitalism with a fossil fuel energy regime which continues unabated today.

8. It is also possible to add a fourth "mini-promethean" revolution to this list. From the 11th to the 14th century A.D. feudal Europe saw the introduction of new agricultural techniques and such a widespread introduction of wind and water power technologies (many of which were first developed in China and the Middle East) that some historians have claimed that a "medieval industrial revolution" occurred (Gimpel, 1977; White, L. Jr, 1965). This revolution was ultimately stillborn as the metabolic rift which expansionary European feudalism opened up ultimately unleashed a process of environmental destruction which led to a crisis of subsistence and demographic collapse in the late 14th century. However, the advances in wind and water power technologies had a number of

long-standing impacts. The development of increasingly sophisticated ship building and navigational technologies in Spain, Portugal and Holland opened up the capacity for Europeans to engage in truly global trade and plundering expeditions which won tremendous new energetic and material stores from vast American and African hinterlands that were to prove pivotal for the development of European empires. Secondly, the mechanical knowledge and capacity developed from the widespread development of wind and water mills went on to play a crucial role in the early stages of the British Industrial Revolution – before fossil fuel energy became widespread – thereby establishing the mechanical basis for large-scale industrial production. [Also check out what Mumford says about the development of the clock as being central to the Industrial Revolution.]

DIMINISHING RETURNS AS A FORCE FOR TECHNOLOGICAL INNOVATION

The two sets of theses we have elaborated above describe together two contradictory tendencies. On the one hand, the more non-renewable low entropy inputs that enter production, the more difficult it should be to find continued stores of such inputs, especially as the dynamic of diminishing returns sets in. And yet, on the other hand, the historical record shows a steady – and since the beginning of the 19th century, an exponential – increase in the global throughput of low entropy energy and materials. How to make sense of such a dynamic?

The perspective that we will be advancing here seeks to relate the growth of the productive forces to the way in which thermodynamic limits condition production process. In this framework, not only do inherently limited supplies of low entropy resources need to be taken into account, but the tendency of the forces of production to grow is understood to be due to the necessary attempt to overcome the dynamic of diminishing returns. In this view, all forms of production which maintain a 'metabolic rift' with nature will be faced with the dynamic of diminishing returns, and thus be required to either increase the capacity of their forces of production, lower their level of subsistence, reduce their numbers through migration or war, or seek the adoption of technological improvements that increase labour productivity and increase the flow of low entropy resources available for consumption. Because the dynamic of diminishing returns only applies to "cases in which technique remains unchanged" (Lenin, 1975: 110), should a society successfully implement technological improvements to its productive process, it will enter a period of increasing returns until the law of diminishing returns re-asserts itself under the pressure of the thermodynamically determined metabolic rift. At this point the society will again have to choose between the options of continued socio-techno evolution, migration and/or warfare with neighbours, or the usually unwelcome option of a decrease in population or living standards (Harris, 1991: 3-7). The tendency for human societies to choose the adoption of technical improvements rather than the alternatives helps to explain why the productive forces tend to grow over the course of human history despite the influence of the second law of thermodynamics. Where a ruling class does not wish to implement this change to the productive forces – perhaps under the impression that by so doing so they will lose social control or otherwise empower subaltern classes – social revolution may become the order of the day. In the words of Marx, when "the material productive forces of society come into conflict with the existing relations of production" there "then begins an epoch social revolution" (Marx, 1859). The development of the productive forces does not invalidate the dynamic of diminishing returns or the effects of the laws of thermodynamics, but merely points to the fact that human beings have, through technological development, been able to continue to access a growing share of the total portion of low entropy materials available on the earth thanks to the growth of the productive forces. How long the productive forces will be able to increase the flow of matter and energy through the production process and how large the metabolic rift between humanity and nature can grow before ultimately undermining any further growth of the productive forces remains an open question.

In hunting-gathering societies, diminishing returns set in after a certain period of time has been spent hunting and gathering in a particular location. Game and wild fruits become scarce as they are consumed, and an increasing amount of labor is required to gather necessary foodstuffs (Boone, 2002). Just as in other modes of production, humans introduced technological innovations to compensate for these declining returns. The anthropologist Marvin Harris describes one example of this process affecting neolithic hunter-gatherers in Mexico's Tehuacan valley some 9000 to 7000 years ago as they began to over-hunt available sources of animal protein.

> As each species was depleted, the hunters attempted to compensate for the declining return in the effort they invested by using more efficient hunting weapons and techniques. Lances, spear throwers, darts, and finally the bow and arrow were pressed into service, all to no avail (Harris, 1991: 34).

Although the labor efficiency – in caloric terms – of hunting was initially increased in the Tehuacan valley through the use of new technology, game soon became so scarce that meat was became a negligible part of their diet. As a result, subsistence efforts shifted towards further reliance on the plants that the hunter gatherers had already begun domesticating and led to the cultivation of new species of maize and beans (Harris, 1991: 34-35). Of course, as long as the human population was small enough and unoccupied hunting grounds remained available, hunter-gatherers could deal with problems of localized scarcity by simply moving on to a different area which had not been as intensively exploited and begin the process again. The fact that for most of human history there was enough space for hunting and gathering societies to relocate while allowing the places that they had hunted out to regenerate, meant that there was relatively little pressure to innovate new technological approaches that increased labor productivity and sped up the human metabolism with nature.

Although the dynamic of diminishing returns operates within all forms of production – because all are forms of metabolism with nature, and because all metabolic relationships are subject to the laws of thermodynamics – the dynamic changes after the Neolithic Revolution when class societies emerge with the development of agriculture. Because hunting-gathering societies couldn't produce an economic surplus – both because of the relatively small amounts of energy and material that were consumed in the metabolism between human beings and nature and because of the impossibility of storing large amounts of food for later consumption – their societies were not marked by class conflict or social relations of exploitation. Individual "big men" arose and gained status as important figures in their community, but their status was primarily psychological and arose as a result of them winning favour by giving away their wealth to other members of the community; they were not able to successfully pass on their political power to their descendants (Polyani; Adams* 1978: 303-304). The ideological assumptions of these societies stressed the fundamental unity between humans and nature and they encouraged methods – such as infanticide and long nursing periods – to keep the human metabolism within the bounds prescribed by nature (Harris, 1991: 22-25). Where serious disagreements or power struggles arose, the aggrieved party could simply move to a new territory and thereby defuse the conflict.

However, after human beings gained increased their capacity to appropriate energy through new energy converters such as domesticated plants and animals following the Neolithic Revolution, human societies across the globe became stratified by class relations once it became possible to store energetic surplus in the form of grain.[31] The elite class that emerged to control this surplus was initially formed by warrior-priests whose religious specialties and knowledge were said to improve agricultural production, or bring divine favour in military conflicts (Childe, 1971). The pace of the human metabolism with nature was no longer regulated by ensuring that all human needs were equitably met through the sharing of food as was the case in the "archaic communist" societies of hunter gatherers, but was sped up as a means of maximizing the societal surplus going to the ruling elite. In various ancient tributary societies such as Babylonia and Egypt, the social surplus was not only directed into hydraulic water works to ensure the continued production of the surplus, but also into great monuments designed to preserve the ideological hegemony of the ruling elite (Mumford; Wittfogel). As the dynamics of class society changed with different modes of production, so did the human metabolism with nature, which is governed by a given set of cultural systems that seek to ensure the social reproduction and/or expansion of a given class society. The 'metabolic rift' that Marx associated with capitalist farming in Britain thus has a much older legacy – it arguably arose with the first use of exosomatic tools and the domestication of fire, but became most strikingly evident with the very rise of agriculture and class society, a fact that is proved by the extensive destruction of topsoil that has been associated with practically every form of agriculture based on the harvesting of annual grains (Dale & Carter, 1970; Jackson, [___]).

With the arrival of class society, the forces of production are dialectically interrelated with the dominant property relations in a given society. Because of the control of the dominant class over the way in which production is carried out, this class can initiate technological changes which it believes will advance its control and share of the social surplus, or it may also stymie particular innovations or technological approaches which hurt its class position. For example, one of the consequences of the "industrial revolution of the Middle Ages" was the widespread mechanizing of fulling practices which were used to overcome the craft monopoly of the towns on making woollen cloth. As Braudel points out "the towns inevitably tried to defend themselves by forbidding weavers working within the walls to have their cloth fulled outside" by the use of water powered mills and he cites ordinances from town authorities in Bristol in the fourteenth century explicitly forbidding such activities (Braudel, 1984: 544). The particular configuration of class forces in a given society thus co-determines the metabolic relationship with nature. The Roman Empire, for example, was driven to continued expansion by the predatory and parasitic nature of the means by which the dominant class appropriated surplus – through slavery and tribute from conquered rivals. Other societies in ancient China, for example, developed a highly productive and intensive agricultural system heavily dependent upon government co-ordinated irrigation projects which held sway despite periodic social collapses produced by demographic and environmental pressures (Wittfogel; Debeir, 1991: 45-47). The means by which surplus was pumped out the direct producers in this model was fundamentally different from the slave based *latifundia* model used by the Roman Empire, and consequently led to a very different metabolism with nature.

Because of important differences in how surplus is appropriated in different class societies, we can no longer talk about the thermodynamic principles of "production in general" to understand the underlying economic logic which regulates the metabolism with nature. But that does not mean that we can ignore the conditions within which a given mode of production establishes its relationship with nature – rather, we must integrate an analysis of the growth of the forces of production with class dynamics and the thermodynamic principles which condition the metabolism of humanity with nature. In what follows we will provide a necessarily limited sketch of the rise of civilization and the ways in which a number of non-capitalist modes of production have produced complex societies on the basis of thermodynamically dissipative structures. This overview will help to prepare us for our detailed examination in chapter 4 of the particular way in which class struggles, metabolic processes, and thermodynamic limits shaped the emergence and evolution of agrarian capitalism in 16th century England.

THE TRANSITIONS BETWEEN VARIOUS PRE-CAPITALIST SOCIAL FORMATIONS

It is a small step from Marx's assertion of the importance of productive forces in transforming modes of production to the argument that one of the most central characteristics of a given mode of production is the way in which it appropriates energy. Marx himself suggested such a causal relationship with his much quoted aphorism that "the hand-mill gives you society with the feudal lord; the steam-mill, society with the industrial capitalist." (Marx, [n.d.]: 109). Transformations of particular energy regimes can then be seen to have wide-ranging impacts on the dynamic of diminishing returns, as well as shaping particular modes of production and the class struggles inherent to them. One of the strongest proponents of the correlation between increasing energy consumption and cultural development was Leslie A. White, a Marxist anthropologist in the evolutionist tradition of Lewis Morgan and Gordon Childe (Pearce, 2004).

White suggested that the level of sociopolitical organization of society was determined by the level of energy production and consumption of a society. If as he argued, the first requirements of any human society is to ensure its own production and reproduction in relationship to its natural environment, and if "everything – the cosmos, man, culture – may be described in terms of matter and energy," (White, 1949: 367) then the technological system by which humans extract energy from the environment "is therefore both primary and basic in importance; all human life and culture rest and depend upon it" (White, 1949: 365). It was on this basis that White argued that the "primary function of culture" was

> …to harness and control energy so that it may be put to work in man's service. Culture thus confronts us as an elaborate thermodynamic, mechanical system. By means of technological instruments energy is harnessed and put to work. Social and philosophic systems are both adjuncts and expressions of this technological process. The functioning of culture as a whole therefore rests upon and is determined by the amount of energy harnessed and by the way in which it is put to work (White, 1949: 367-368).

In adopting a theoretical standpoint such as White's, grand moments of energy transition – the "Promethean revolutions" which Georgescu Roegen identified – the domestication of fire, the development of agriculture, and the invention of the heat engine, become momentous turning points in the history of human development.

The origins of the oldest of these revolutions, the discovery and use of fire, is lost in the mists of time some 400,000 years ago, but it is undeniable that it represented a qualitative step forward in the human appropriation and conversion of energy. By converting mechanical motion into heat (through the rubbing of pieces of wood together) human beings learned to produce fire when and where they needed it. As Engels pointed out, "the making of fire with friction was the first instance of men pressing a non-living force of nature into their service" and was "the first great victory of mankind over nature" (Engels, 1976: 79-80). By 100,000 years ago fire was universally used across all human societies and represented "the first great active human interference with natural processes" as humans "brought fire to parts of the planet where it seldom or never burned spontaneously [and] tried to banish it from places where without human interference it would have burned repeatedly" (Goudsblom, 2002: 29). The use of fire in this way helped to shape local ecosystems in ways that were more conducive to human needs, by increasing the habitat for grazing herbivores or clearing out underbrush to allow for the growth of berries and other edible plants.

With the use of fire, humans could keep warm in colder climates, eat new kinds of food, scare off predators and preserve food for later consumption. Fire allowed humans to modify their landscape on an unprecedented scale through the use of controlled burnings, and some scientists have speculated that the widespread use of fire in the Pleistocene may have affected the atmosphere and been responsible for changes to the global climate.[32] As a source of thermal energy, fire allowed for the production of "a new space reserved for humans – the hearth and its surroundings" with profound social and cultural implications (Debeir *et al*, 1991: 10). The control over energy gained by humans through the use of fire can thus be seen to have played a fundamental role in the evolution of human cultural complexity – and even in the development of human societies *per se*.

Of course, the essential limitation to fire is that the energy it provided was in the form of heat and not of motive power. Except in clearing land, it could not substitute for or replace human labor. As Engels pointed out,

> many thousands of years must have elapsed between the discovery of fire by friction and the time when Hero of Alexandria (ca. 120 BC) invented a machine which was set in rotary motion by the steam issuing from it. And almost another two thousand years elapsed before the first steam engine was built, the first apparatus for the conversion of heat into freely usable mechanical motion (Engels, 1976: 80).

THE NEOLITHIC REVOLUTION: THE SECOND "PROMETHEAN REVOLUTION"

With access to only simple stone tools and control of fire, human cultural evolution proceeded slowly. Consequently, there was very little technological or social change for hundreds of thousands of years after the development of fire. But some 400,000 years after the first "Promethean Revolution," a second and much more wide-ranging transformation of the human metabolism with nature occurred. Dubbed the Neolithic Revolution, White described it as follows:

> after hundreds of thousands of years of relatively slow and meagre development during the Old Stone Ages, cultures suddenly shot forward under the impetus of augmented energy resources achieved by agriculture and animal husbandry. Great cities, nations, and empires took the place of villages, tribes, and confederacies as a consequence of the agricultural revolution (White, 1949: 372).

The Neolithic Revolution arose independently in half a dozen different world centres as human beings developed the capacity to domesticate and breed specific traits into various plants and animals. In order of appearance, these centres of agricultural development occurred as follows: in the "fertile crescent" of western Asia approximately

10,000 years ago; in New Guinea about 10,000 years ago; in southern Mexico between 9000 and 4000 years ago; in the loess plains alongside the Chinese Yellow river about 8500 years ago; in the Peruvian or Ecuadorian Andes some 6000 years ago, and in the middle Mississippi basin between 4000 and 1800 years ago (Mazoyer and Roudart, 2006: 76). One major factor accounting for the rise of agriculture at this time was no doubt the termination of the last ice ace. These forms of agriculture (with the exception of the New Guinean complex) were based upon the domestication of carbohydrate rich seed-based annuals which thrived in moments of ecological upheaval that wiped out rival plant communities. The global warming and catastrophic flooding produced by the release of glacial melt would have provided excellent conditions for these grains to achieve ecological success (Manning, 2002: 28).

It is unclear if agriculture first developed as a means of providing domesticated animals with grain, or if hunting-gathering societies increasingly turned to cultivating wild grains before they domesticated animals (Ponting, 1991). In either case, the scientific consensus now holds that the emergence of agriculture was a protracted process in which many hunter-gatherers engaged in limited forms of cultivation and in which many cultivators continued to hunt and gather wild foodstuffs. There is no one agreed upon explanation for the shift to agriculture from hunting-gathering. Some archaeologists suggest that the shift was driven by population pressures as hunting-gathering societies pushed against subsistence levels, others suggest that changes in climate led to pastoralism and irrigated forms of cultivation (Harris, 1991). Still others suggest that the decisive change likely occurred as populations which had been successfully experimenting with agricultural practices were no longer able to return to their former means of subsistence, and that their significantly increased populations faced the choice of going hungry or increasing their labor productivity through intensifying agricultural practices.

> …in the centres of origin of Neolithic agriculture, it is probable that the sedentary populations grouped into villages of rapidly increasing size, each exploiting a defined territory, one day or another came up against the limits of this territory's exploitability by simple predation. From that moment, the necessary time to gather and hunt overexploited wild species became greater than the necessary time to cultivate and breed them. As the technical (tools) and ethological (sedentary living) conditions were already brought together, proto-cultivation and proto-breeding became from that moment more advantageous in these places than simple predation (Mazoyer and Roudart, 2006: 84).

From the standpoint of the societies engaged in it, agriculture had three major advantages over hunting and gathering: firstly, with a greater input of human labor it allowed a smaller area of land to produce significantly more food and thus support a larger population; secondly it allowed for food in the form of grain supplies to be stored over a long term, thereby ensuring against periodic famines; thirdly, the storable surplus that it produced allowed for greater labor specialization and the higher development of the productive forces – especially through the development of primitive metallurgy and more sophisticated forms of stone tool production (Childe, 1971: 86).

What made agriculture a "Promethean Revolution" is that as long as soil fertility could be maintained, it produced a self-sustaining increase in the flow of low entropy energy and materials that could be directed into human consumption. Selective breeding encouraged plants to put their energy into producing carbohydrate rich seeds, while domesticated animals became, in effect, a kind of "exosomatic" organ in the service of humanity. For with the domestication of sheep, goats and cows, human beings effectively controlled the stomach organs of ruminants and used them as energy converters which could turn the cellulose in plants – which is undigestible by humans – into usable low entropy energy and matter – whether in the form of food such as meat and milk, raw materials such as leather or wool, or sources of motive power for transport or traction for early machines such as the plow and mill (Georgescu-Roegen, Lotka).

Although the domestication of animals gave nomadic pastoral groups the capacity to drastically increase their numbers on hitherto marginal lands, it was the cultivation of energy rich cereals and legumes which ultimately gave rise to civilization. As White argued, "all of the great civilizations of antiquity were brought into being by the cultivation of cereals; no great culture has ever been achieved independently of the cultivation of cereals" (White, 1949: 371). Cereals were important not only because they were energy rich [33] and capable of being stored over the long term, but also because they gave such a great return on the energy invested in their cultivation. Early documentation dating from the Sumerian civilization some 4500 years ago indicated that farmers sowing barley managed on average to produce a yield 86 times higher than the seed grain they used, while the ancient Greek scholar Herodotus claimed that when he visited Babylonia, the cereal yield was an astounding 200-300 times greater than the amount sown (Childe, 1971: 98; Debeir et al, 24). These new agrarian civilizations were not solely based on a singular grain, but domesticated a series of plants and animals which provided a wide range of cultural-technical benefits. Central to the success of the near Eastern, Chinese, and Central American agricultural centres was a vegetable complex which "consisted of a grain that supplied glucides, a legume that supplied proteins, and a plant that provided textile fibres" (Mazoyer and Roudart, 2006: 84). Human beings had begun a process of co-evolution with a carefully selected number of domesticated species that produced mutually beneficial results.

But the shift to agriculture did not overcome the problem of diminishing returns. With little in the way of technical knowledge of maintaining soil fertility, most early Neolithic experiments in agriculture were only able to produce a few years worth of crops on land which then had to be abandoned in order for it to regain its fertility (Williams, 2000: 31). As a result, this early stage of agriculture resembled "slash and burn" forest agriculture, and because it had to remain constantly on the move, it did not lead to the founding of lasting cities or states (Hyams, 1976: 53). The real breakthrough required for the emergence of the first civilizations, was not simply cereal cultivation but an agricultural setting in which the exhaustion of the soil was not an issue and in which the problem of diminishing returns could be pushed far into the future. Humanity made that breakthrough by applying its early agricultural knowledge to crop production on several great alluvial plains, where rivers deposited vast quantities of nutrient rich topsoil which replenished the soil despite repeated cultivation.[34] It is thus no accident that the most successful Bronze Age civilizations, and the emergence of what Gordon Childe called the "urban revolution" developed independently on settlements on the deltas of major river systems like the Nile, Euphrates, Tigris, Indus and the Yangtse and Hwang-ho. The tremendous amount of alluvial soils carried down these river systems constantly renewed the top-soil depleted through agriculture and made possible long term cultivation over millennia (Hyams, 1976: 43-54).[35] As Harris points out, these regions also share a further similarity, in that each of "the six most likely regions of pristine state development… possess markedly circumscribed zones of production" – i.e. they are fertile valleys or alluvial deltas surrounded by desert or dry zones (Harris, 1991: 117).

The great technical gains of this "urban revolution" – population concentration in cities, written languages, the invention of coinage, astronomy, and the development of political culture – came as a result of human settlements in settings which were capable of a very productive agriculture which could be apparently renewed indefinitely.[36] In these alluvial civilizations, the regenerative powers of the silt carrying waters forestalled the growth of a metabolic rift between humanity and nature. It should also be noted that agriculture on such plains had ready access to water which with the appropriate irrigation works could be used to reliably provide the enormous amounts of water that cereal production requires. As Debeir et al note,

> most plants need 300 to 1000 kg of water to synthesize 1 kg of dry matter. Wheat for instance, requires 400 to 500 kg of water to produce 1 kg of dry matter (seeds, stems, roots), that is, more than a ton of water for a single kilogram of grain. In energy terms, the worker's daily cereal ration, that is 4000 kcal, requires plants to pump about 1 ton of water. Plant converters make optimal use of solar energy only with water, the fluid carrying nutrients from the soil to the plant (Debeir et al., 1991: 22).

The extraordinary agricultural productivity of alluvial civilizations made up for the fact that they lacked both mineral resources such as copper and tin, and had little in the way of timber and stone supplies. The river system provided a highly effective means of transport, and the civilizations developing on the deltas of these rivers became important hubs of regional trade and exchange. As the population and political strength of these early centres of civilization grew, a dynamic soon emerged that saw them reach into their hinterlands to trade the products of civilization (alcohol, pottery, textiles, bronze tools and weapons) for raw materials unavailable in the city centres. This is essentially the first development of what Moore (2010) calls a "resource frontier." As non-civilized tribes fell within the sphere of influence of urban populations they transformed their own social relations in order to gain advantage from the advances of civilization. By 3000 BC professional merchants in the Mesopotamian city states were transporting copper and building stone from Oman, timber from Syria, tin from Drangiana in eastern Iran, silver and lead from the Taurus mountains, mother-of-pearl from the Persian Gulf, sank shells from peninsular India, and amulets, beads, and pottery from the Indus valley civilization (Childe, 1971: 104 and see De Vries, 2002: 177-179). This impetus for trade received a powerful stimulus from the unprecedented growth in population made by these early civilizations. The Babylonian Empire under the rule of the Amorites cultivated at least 10,000 square miles of land through its irrigation system, and maintained an unprecedentedly large population of between 15 and 20 million people (Dale & Carter, 1955: 44).

The development of these new societies provide an interesting example of the way in which class dynamics informed the development of the productive forces. As these civilizations emerged and began to produce large surpluses, increasing technological knowledge and labour co-ordination was required to keep production going. Large-scale irrigation works were devised to increase and maintain agricultural productivity, and seasonal changes needed to be accurately measured to ensure that planting and harvesting occurred at the appropriate times. For this, detailed astronomical knowledge was required, thereby producing the ancestor of our modern calendar. Class structures were further cemented as a priest-class arose to coordinate the more complicated forms of agricultural production required to sustain a burgeoning population. Military expeditions against nearby rivals and barbarian peoples on the outskirts of empire provided slaves that could be put to work in maintaining irrigation works or other forms of manual labour. The development of technologies such as the written language first emerged as a requirement of class rule, as this technology was initially deployed as a means of keeping track of the accumulation and distribution of surplus stored in the granaries of these new city states. From a Marxist perspective, even these new technologies which were originally deployed for the narrow class interests of one section of society managed to play a historically progressive role by allowing for new possibilities of human freedom and self actualization (Cohen, 2002).

This process of conquest and the development of trade gave rise to further development on the periphery of these city states. As "barbarian" tribes benefited from the technological advances of civilization, they periodically developed new means of harnessing energy and building exosomatic weaponry that gave them the upper hand in warfare against early civilizations. The Hyksos utilized compound bows and horse-drawn chariots to successfully invade Egypt's upper delta in 1710-1720 BC and were only defeated when the Egyptian pharaohs began to utilize similar military technology against them. Likewise, the domestication of horses on the Western Asian steppe and the use of the recurve bow led the Mongols to develop a highly mobile and powerful military force that ravaged civilizations from China to Europe.

Ultimately, what spelled the end of the Bronze Age civilizations ushered in by the Neolithic Revolution was the development of new weapon and toolmaking technology that dramatically increased labour productivity and military prowess. The smelting of iron requires the expenditure of much larger amounts of energy than copper or tin, but it produces much more effective weapons and tools. Success in producing any significant amounts of iron – which is readily available in much of the Earth's crust – thus requires ready access to wood supplies, an energy resource that was largely lacking in the homelands of the great alluvial civilizations of the Bronze Age. However, on the margins of these civilizations, the Assyrians and Hittites had access to large swaths of hardwood forests, and with the iron produced thanks to these energy resources they were able to successfully outcompete older Bronze Age civilizations. As Childe notes:

> Cheap iron democratized agriculture and industry and warfare too. Any peasant could afford an iron ax to clear fresh land for himself and iron plowshares wherewith to break up stony ground. The common artisan could own a kit of metal tools that made him independent of the households of kings, gods, or nobles. With iron weapons the commoner could meet on more equal terms the Bronze Age Knight. With them too poor and backward barbarians could challenge the armies of civilized states whose monopoly of bronze armaments had made them seem invulnerable (Childe, 1954:191).

Consequently, the rise of the Iron Age saw a shift in the centre of power towards the Mediterranean basin where greater supplies of wood were available to smelt iron tools and weapons (De Vries, 2002). However, this shift also saw a return to the metabolic rift which had first limited the development of urban civilization to the alluvial plains. Iron technology drastically increased labour productivity and allowed agriculture to be extended into new territories, but this extension of agriculture created problems of deforestation and overgrazing. In the Armenian hills and mountains where Mesopotamia's life giving rivers originated, widespread deforestation dramatically increased the flow of silt downriver and contributed to the blocking of the irrigation canals that were so essential to the productivity of Mesopotamian agriculture[37] (Dale & Carter, 1955: 43-53). Mesopotamian civilizations were repeatedly overrun by barbarian invaders using this iron age technology, and although conquerors such as the Assyrians, Persians, Greeks, Parthians, Muslims, Turks, and Mongols had differing relationships to the upkeep of the complex irrigation systems of Mesopotamian society, the end result of the Iron Age technology unleashed by the barbarians on the periphery of Mesopotamian civilization spelled the demise of this cradle of civilization. Because the invaders failed to take steps to control the metabolic rift produced by human clearing of lands in the headwaters of the Euphrates and Tigris, large amounts of topsoil washed down the rivers and the peasant and slave labor so necessary for keeping the irrigation channels clear was unable to keep up with the increased flow of silt. The flow of topsoil was so great that it pushed the delta of the Euphrates 120 km further into the Persian Gulf. By the time Mesopotamian civilization finally lost its battle with diminishing returns, its irrigation canals were bordered with piles of silt thirty to fifty feet high, and this formerly lush breadbasket of civilization had become arid desert (Dale & Carter, 1955: 52). The civilization of the Indus valley suffered a similar fate, following the invasion of pastoral Ayran tribes its civilization was buried under mountains of silt displaced from topsoil upstream caused by unsustainable logging and agriculture.

While the expansion of agriculture and civilization beyond the original alluvial civilizations of the Bronze Age was able to produce productive agricultures with large ecological surpluses, these ancient societies were unable to build permanent civilizations, largely because of the long-term consequences of the metabolic rift they opened up with nature. Despite all of its grandeur and accomplishments, ancient civilizations tended to leave unproductive agricultures and sometimes empty deserts in their wake. As Dale and Carter point out:

> historical records of the last 6000 years show that civilized man, with few exceptions, was never able to continue a progressive civilization in one locality for more than 30 to 70 generations (800 to 2000 years).… After a few centuries of growth and progress in a favourable environment, his civilizations declined, perished, or were forced to move to new land. The average lifespan was 40 to 60 generations (1000 to 1500 years). In most cases, the more brilliant the civilization, the shorter was its progressive existence. These civilizations declined in the same geographical areas that had nurtured them mainly because man himself despoiled or ruined the environments that helped him develop his civilizations. (Dale & Carter, 1955: 7-8).

If soil fertility wasn't ruined, it was possible for an empire or region to bounce back from setbacks caused by political infighting or barbarian invasion. However, once the land that of civilization depended upon for its agriculture declined, so did the civilization.

The Egyptian and Sumerian civilizations gave way to the Akkadian and Assyrian civilizations which were able to produce iron weaponry and tools. The Mycenaean civilization based in Crete became the next regional hegemon, but it too suffered from extensive problems of soil erosion and collapsed largely from its ecological contradictions ([source]). The cutting edge of civilization then moved to the Greek city states by 500 BC where a new method of poly-culture involving the growth of cereals, vines, and olive trees allowed for the development of a dynamic new agriculture. However, because of the ecological limits imposed by the hilly terrain and relatively erosion prone topsoil, Greek city states had trouble producing enough foodstuffs to feed their population.

The Athenian city-state was the prototype of a new urban order un-apologetically based on the metabolic rift: for the first time in history a dominant regional state did not produce enough food to sustain itself, but rather chose to specialize in a few key forms of export-based production – primarily the production of olive oil and silver by slave labor –

and then received grain in trade or as a form of tribute from nearby societies that it dominated (Childe, 1971: 244, Debeir et al. 1991, 29). Ultimately, population growth and problems with declining soil fertility led the Greek city states and other Mediterranean cultures such as the Etruscans, Mycenaeans, and Phoenicians to practice seaborne colonization by sending out significant portions of their population to build colonies in other more fertile areas of the Aegean, Adriatic, Black and Tyrrhenian seas, as well as on the North African, French and Spanish shores of the Mediterranean.

Despite some attempts to control soil erosion, attempts to overcome the metabolic rift within these societies largely failed. Lebanon, the home of the Phoenicians, was famous for its cedar trees, which were highly sought after as a form of raw material by empires along the Mediterranean coast and beyond. The destruction of Lebanon's forests as well as those surrounding the Mediterranean basin changed the local ecology, affected the capacity of the surrounding soil to attract and hold moisture, and eventually led to desertification when the weakened ecosystems faced over-grazing from bovids. Evidence of this large-scale ecological destruction around the Mediterranean is reflected in many ancient texts. The following passage from Plato, in which he talks about the ecological disruption wrought in Attica is one of the best known.

> What now remains of the once rich land is like the skeleton of a sick man, all the fat and soft earth having wasted away, only the bare framework is left. Formerly, many of the present mountains were arable hills, the present marshes were plains full of rich soil; hills were once covered with forests, and produced boundless pasturage that now produce only food for bees. Moreover, the land was enriched by yearly rains, which were not lost, as now, by flowing from the bare land into the sea; the soil was deep, it received the water, storing it up in the retentive loamy soil; the water that soaked into the hills provided abundant springs and flowing streams in all districts. Some of the now abandoned shrines, at spots where former fountains existed, testify that our description of the land is true (Plato, ___).

THE RISE AND FALL OF ROME

With the decline of the Greek city states following their absorption into the Macedonian empire and the fragmentation of that empire following Alexander's death in 323 BC, the Roman empire arose as the dominant civilization in the Mediterranean. Evidence suggests that Rome, which was founded in 753 BC as one small kingdom amongst many in the Latium region of western Italy, was initially blessed with extremely fertile soil. There are more than 50 now-extinct volcanoes within a 25 mile radius of Rome, and the ash released from these volcanoes over millennia helped to provide a soil with high quantities of nutrients essential for plant growth (Frank, 2004: 7). The rich Roman soil enabled a highly productive agriculture that was capable of supporting a large and dense population. At the time of its founding as a republic in 508 BC, Rome controlled only 400 square miles of territory, but had a estimated total population of 400,000 giving it a population density of about 1000 people per square mile (Dale & Carter, 1955: 125). Even a population half this size would be uncommonly dense, and historians agree that Rome must have had a highly productive agricultural system (and likely one that managed to feed more people by virtue of providing a mostly vegetarian diet) in order to maintain this population.

As Rome grew in power it began to champion the cause of nearby Greek colonies in their confrontations with the Carthaginian Empire. This led to a series of conflicts between the Romans and the Carthaginians culminating in the three Punic Wars which took place between 264 and 164 BC. In the second Punic War, the Italian peninsula was invaded by the talented Carthaginian military commander Hannibal, and war was waged back and forth across the Roman countryside for more than 16 years. The result of this long-lasting military conflict – in which each side sought to deny the fruits of the land to the other through scorched-earth tactics – had the result of driving Roman yeoman farmers from the land and destroying what Hyams calls the "Roman soil community." From this point on, Roman cities on the Italian Peninsula were unable to produce enough grain to feed their population and turned to grain imports to make up the shortfall (Hyams, 1976: 135; and Dale & Carter, 1955: 130). In addition to the destruction of agriculture, much of the forests in the Italian peninsula were cut down for war material including the building of ships for the Roman fleets that challenged the Carthaginian navy (Williams, 2000: 35). It was at around this time that malaria began to develop in Italy, a consequence of the new marshes being produced at the mouths of major rivers from all the topsoil flushed downstream due to deforestation, over-grazing and unsustainable agriculture. Unable to defeat Hannibal on the Italian peninsula, Rome eventually won the war against Carthage by invading North Africa, but with the Roman countryside devastated, this victory marked a fundamental turning point in Roman history.

After its victory over Carthage, Rome began a process of rapid expansion, and by 117 A.D. Rome had become master of the Mediterranean world. Roman expansion was financed by plunder, and this process transformed both the Empire's agriculture and its finances.

> In 167 BC the Romans seized the treasury of the King of Macedonia, a feat that allowed them to eliminate taxation of themselves. After the kingdom of Pergamon was annexed in 130 BC, the state budget doubled, from 100 million to 200 million sesterces. Pompeii raised it further to 340 million sesterces after the conquest of Syria in 63 BC. Julius Caesar's conquest of Gaul acquired so much gold that this metal dropped 36 percent in value (Tainter, 1988: 129).

On the agricultural front, the defeat of Carthage brought major changes to how Rome fed itself. From Carthage, Rome borrowed the agricultural techniques of slave-based agricultural production, which Carthage had used to successfully produce great ecological surpluses from the then highly fertile lands along the North African coast. Carthaginian society was largely based on trade and warfare, and had no independent peasantry, but carried out an intensive form of plantation cultivation by slave labour. Hyams argues that the Romans appropriated this method of industrial production "which took no account of soil as such, and was concerned with getting the largest possible crops out of the soil" and that while this social organization of agricultural production was profitable, the damage it did to the soil ultimately undermined the Roman Empire (Hyams, 1976: 130).

Before the Punic wars, slavery in Rome was primarily reserved for small scale domestic work and was associated with the patriarchal family unit. After the Punic wars, the Roman economy became increasingly reliant upon large scale slave-based agricultural production. In part this change was motivated by the vast inflow of hundreds of thousands of enslaved Carthaginians to the Roman Empire.[38] By some estimates, the total population of Italy grew from about 4 million people at the beginning of the second Punic war to about 7 million people by the reign of Augustus – with the vast majority of this increase coming from the influx of captured slaves (Konstan, 1975: 161).

The growth of slavery was further encouraged by the displacement of the Roman peasantry from the Italian mainland during Hannibal's invasion (Hyams, 1976: 130). Because of the damage to the old form of small peasant farms, and the comparatively much cheaper avenues for grain production in new Roman provinces in Sardinia, Egypt and North Africa, the *latifundias* on the Italian mainland after the second Punic War tended to produce olive oil and wine rather than cereals. Some in fact imported foodstuffs to feed their slaves (Dale & Carter, 136). By the first century A.D. North Africa and Egypt were the granaries of the Empire and some 12,000 ships a year were transporting millions of hectolitres of grain to Rome from across the Mediterranean basin (Debeir et al. 1991, 35-36).

In A.D. 117 the Roman Empire had expanded to its maximum limits. There were no further civilizations on its borders which it could force to provide tribute or conquer to replenish the slave population working on its *latifundias*. The dynamics of increasing returns that had served Rome so well in the ascending phase of its growth now became a liability as no new sources of slaves were available, and there were no new areas of land available for Roman agricultural technology to expand upon, while the advantages of the Roman road network were negated by the far-flung nature of the Empire and the prohibitive cost of transporting goods overland. As Debeir et al. put it:

> During the ascending phase of the cycle, each new conquest had extended the area from which Rome drew its power by levying food and slaves. This cycle reached its peak when all possibilities of navigation in the Mediterranean world and all coastal resources had been thoroughly exploited. Then, the distances between the coasts and the more continental hinterland of occupied regions became such that overland transport to the legions stationed on

> the borders absorbed all the surplus levied from the margins of the Empire (Debeir et al, 1991: 40).

Slavery was certainly lucrative, but as a labour-regime it stymied innovation and prevented the introduction of new technologies or methods of increasing labor productivity. Because of the centrality of slave labour to production, "the social incentive to develop machines powered by other sources of energy than humans was weak or nonexistent" (Debeir et al., 1991: 38; Braudel, 1984: 543). The Romans did have experience with waterwheels used in grinding grain, but the introduction of labor-saving technology was typically discouraged by the Roman ruling class which preferred existing social-technological relationships The (Gimpel, 1976: 9). As Childe points out, despite its magnificent engineering accomplishments, Rome made no new contributions to the advancement of science, and "had not released any new productive forces and did not materially expand the use of those already available in the Hellenistic age" (Childe, 1955: 280). Not only did Rome import most of its food, it also imported most manufactured articles (Dale & Carter, 1955: 137)

As Roman decline accelerated, evidence of the increasing metabolic rift comes into the historical record. Emperor Domitan (81-96 AD) was so concerned about the decline of cereal production that he forbade the planting of grapes in Italy and demanded that each landowner in the non-Italian provinces should destroy half of his grape vines and produce grain instead (Dale & Carter, 1955: 137). By 193 AD the emperor Pertinax offered free land and ten years of tax exemption to any citizen of the empire who would occupy and farm vacant land but "he found few takers who were willing to homestead the eroded, worn-out, abandoned land scattered over Italy and many of the provinces" (Dale & Carter, 1955: 141). Emperor Diocletian (284-305 AD) in his attempt to reorganize the Empire, issued an edict seeking to bind free farmers and slaves to the land, and Emperor Constantine made it a crime for the son of a farmer to leave the land on which he was born.[39]As historian Karl B. Mickey wrote, by the time of the fall of the Western Roman Empire in 476 AD,

> the agricultural regions of Italy and the provinces were nearly depopulated. Part of the depopulation was due to low birth rates and the rest to the abandonment of the land by its cultivators. Efforts were made to stem the trend, by paying bounties to parents for each new birth and by passing laws binding both the slaves and *coloni* (free tenants) to blend. But all efforts failed; the exhausted, eroded soil simply could not support the population and the terrific weight of imperial taxation (Mickey, 1945: 138).

Because the social structure of the predatory, slavery based production system of the Roman empire tended to inhibit the development of new technologies which could increase labour productivity and thereby overcome the tendency towards diminishing returns, and once Rome grew to its territorial limits, its decline and eventual fall were inevitable. Eventually this combination of declining marginal returns meant that there was no longer much economic gain to be gathered from holding onto the Empire, and it simply collapsed into its smaller constituent parts (Tainter, 2004).

In its collapse, the Roman Empire laid the framework for the future development of feudalism in Europe. Attempts to bind peasants to the land through imperial decrees led to the kind of self-sufficient manorial style of social organization that produced the characteristic feudal estates of Western Europe (Frank, 2004: 255). Northwestern and central Europe had fertile, largely uncultivated soil, but the heavier make up of this clay soil required substantially different agricultural practices than those used around the Mediterranean basin, and it was not until the introduction of the heavy plow and the horse collar in the 11^{th}-century that Western European agriculture really took off (Mazoyer and Roudart, 2006: 217-309).

If White considered human culture as a social evolutionary mechanism to capture increasing flows of energy, the anthropologist Joseph Tainter investigated the question of what happened when human societies face stagnant or diminishing inputs of energy into their civilization. Tainter posited that levels of complexity (as defined by the division of labor and the number of "distinctive parts or components" present in a society) were correlated to the available flow-through of energy in that society.

> Human societies and political organizations, like all living systems, are maintained by a continuous flow of energy. From the simplest familial unit to the most complex regional hierarchy, the institutions and patterned interactions that comprise a human society are dependent on energy. At the same time, the mechanisms by which human groups acquire and distribute basic resources are conditioned by, and integrated within, sociopolitical institutions. Energy flow and sociopolitical organization are opposite sides of an equation. Neither can exist, in a human group, without the other, nor can either undergo substantial change without altering both the opposite number and the balance of the equation. (Tainter, 2004: 91).

Tainter argued that the greater the energy flow in a society, the more complex and developed a sociopolitical organization of the society can be. Increased forms of complexity – such as a division of labor and specialization in particular trades – can help to overcome internal contradictions within a society, spur technological and advancement to acquire even more energy resources, and aid in conflicts with rival societies. Tainter's perspective is thus quite similar to the framework used by ecologists such as H.T. Odum in their study of energy flow in ecosystems. Odum, in building upon Lotka's work, argued that the Darwinian concept of natural selection favoured species which were able to maximize the amount of energy they could capture from their environment. With greater flows of energy an ecosystem can develop greater differentiation and systemic complexity. Odum pointed out the much higher number of species in tropical rain forest environments where the solar energy striking the earth was most intense and where the ecological system had best adapted to circulating this flow of energy. [[Find material from Odum.]] In the case of human societies, Tainter argued that societies co-evolved with nature based on the amount of the available energy humans could capture. Until the development of the Industrial Revolution, the flows of energy in human societies were primarily determined by agricultural production.

Central to Tainter's argument is his claim that "energy flow and sociopolitical organization must evolve in harmony" (Tainter, 2004: 91). If forms of sociopolitical organization become too complex and "top heavy" in comparison to the energy flows which support them, then such a society will become prone to "collapse" or the swift reduction of social complexity. Tainter identified the main cause for the disjuncture between energy flow and sociopolitical organization as stemming from the law of diminishing returns which he described as "one of the few phenomena of such regularity and predictability that economists are willing to call it a law" (Tainter, 2004: 92). As applied to the development of social systems, the law dictates that at a certain point "higher amounts of this investment [in complexity] will yield smaller increments of return" (Tainter, 2004: 92). Tainter suggested that the law of diminishing returns (which produces a bell-like curve) applies not only to nonrenewable resources such as fossil fuels and renewable resources (such as the soil, forests, or fisheries) which are used up more quickly than they can regenerate, but also to a wide range of more complex and "immaterial" sectors of the economy.

> Patterns of declining marginal returns can be observed in at least some industrial societies in the following areas: agriculture, minerals and energy production, research and development, investment in health, education, government, military, and industrial management, productivity of GNP for producing new growth, some elements of improved technical design.... Such observations are not a full monitor of the marginal return that any particular society is experiencing overall on investments in complexity. There may be favourable countertrends in some spheres, perhaps such as microprocessor technology. Yet there can be no denying the disquieting nature of the statistics.... (Tainter, 2004: 211).

Because of the effect of the law of diminishing returns on the energy resources which are so central to the establishment of complex societies, Tainter argued that complex societies always face a potential threat of collapse. The problem of diminishing returns can of course be overcome with new technological innovations or with the discovery of new resources and technology which allow for the throughput of energy and materials to be increased, but without regular breakthroughs that produce qualitatively improved energy systems, the law of diminishing returns will continue to cast its foreboding shadow over civilization. In Tainter's model, great civilizations like Rome collapse when the costs of maintaining their complex superstructures with their armies, long chains of command, and growing state bureaucracies prove too costly to maintain given the declining flow of energy and resources going into the economic base of society.

Leslie White and Joseph Tainter were thus able to provide a thermodynamic explanation for the rise and fall of human societies. White neatly summarized his argument as follows: "We can now formulate the basic law of cultural evolution: other factors remaining constant, culture evolves as the amount of energy harnessed per capita per year is increased, or as the efficiency of the instrumental means of putting the energy to work is increased" (White, 1949: 368-369). Tainter's conception of civilizational collapse is simply the inverse of this perspective – arguing that as the capacity to incorporate energy subsidies into a civilizational matrix declines, so does the social level of organization it is possible to maintain. Taken together, these approaches seem to offer an explanation of the exponential rise of human numbers and cultural power as well as a powerful warning of what a future of energy and resource scarcity might bring.

THERMODYNAMICS AND TECHNOLOGICAL DETERMINISM

The thermodynamic analysis of White and Tainter has a lot to recommend itself. It accounts for the rapid rise of the human species through the appropriation of new forms of energy, and it underlies the centrality of energy to our own very complex societies. Such an approach can explain how the great Bronze Age civilizations achieved an unprecedented level of civilizational complexity, and by referring to the problems of maintaining agricultural production in conditions of a metabolic rift, it can explain both the tendency to improve the forces of production in order to overcome diminishing returns, and the periodic "dark ages" that have occurred where this improvement has proved impossible. The inability of salinized or highly eroded soil to produce an agricultural surplus on lands which have been ruined by the metabolic rift also explains the shift of civilizational development away from Mesopotamia and later the Mediterranean coast. This analysis is also extremely useful for pointing out the steady increase in exosomatic energy controlled by humans. The new capacities unleashed by the horse collar, the "industrial revolution" of the Middle Ages which saw an unprecedented use of wind and water power (Gimpel, 1977), and the use of wind power with new shipbuilding techniques which allowed European sailing vessels to circumnavigate the world can thus be seen as increasing the energetic throughput of the forces of production and thereby setting the groundwork for the evolution of capitalist society.

And yet at the same time, this approach, especially when it is examined in primarily energetic terms ends up replicating many of the teleological errors associated with liberal and Marxian historiography (Brenner, 1989). This teleology is also present in ecological histories which stress societal growth as resulting from increases in energetic consumption. White seems to recognize this problem but is unable to resolve it. On the one hand, in describing the way in which the technological capacity to control energy transformed human societies, he argues that "the technological factor" is determinant of cultural systems, social systems, ideology and philosophy. While culture may "condition" the technological system, "to condition is one thing; to determine, quite another" (White, 1949: 366). But then, in discussing the social stagnation that set in after the major advances produced by each energy revolution (when as Tainter would have it, the marginal returns on investment began to decline), White seems to contradict himself by suggesting that the social system contained technological process and brought "further progress in culture as a whole virtually to a standstill" for centuries (White, 1949: 382). White uses a Marxist class analysis to argue that the stagnation affecting the great Bronze Age civilizations and various forms of feudalism was attributable to the way in which the parasitical ruling class appropriated the wealth produced by peasants and slaves.[40] The producing class, who had ready access to the means of production, gained no advantage if they were to develop new technologies to increase their output – their overlords would simply appropriate a larger amount and leave them the bare necessity required for subsistence. Similarly, the ruling class did not imagine long-range plans to improve agricultural production because of the nature of their immediate needs and the possibilities of acquiring new lands and treasure through warfare and plunder (White, 1949: 382). Given that these periods of stagnation were able to resist the introduction of new technological factors for hundreds and sometimes even thousands of years, a historical materialism focused on the energetic underpinnings of energy transitions has to pay very close attention to class conflict and the means by which the different social classes provide for their own reproduction.

The thermodynamic approach to history can easily fall into a teleological trap of simply explaining growth and development as an inevitable consequence of the unlocking of energy resources. In doing so, this approach can take on either capitalist or socialist teleologies. In the case of the former, an argument that increasing energy inputs allow for social advance through the increasing division of labor and consequent development of complex societies, echoes Adam Smith's argument in the *Wealth of Nations* that the division of labor is the central force in producing capitalist growth and development (Brenner, 1989). Such an approach undermines the contingencies of class struggle, and offers little insight as to the dynamics occurring within the all-important moments of transition between energetic and productive regimes. In the case of the latter, technology is seen as the motor force in altering the forces and in turn the relations of production, and this conceit led Stalinist technocrats to seek to increase the forces of production at tremendous human and ecological cost under the mistaken assumption that to do so would automatically lead to a communist utopia.

In contrast, the thermodynamically aware historical materialism that we are trying to develop here must be able to account for the moments of ecological, energetic, and social transitions that occur with the changes between modes of production. The transition inaugurated by the shift to fossil fuel energies and the rise of capitalism was one of truly epochal proportions, rivalling the Neolithic Revolution and its impact on nature and human social organization. It is to the examination of this unique transformation that we will now turn.

CHAPTER 4 - CLASS, ENERGY AND ECOLOGY IN THE RISE OF FEUDALISM

Beginning with Edward Gibbon's Decline and Fall of the Roman Empire, many historians have dismissed the whole of the Middle Ages (from the abdication of emperor Romulus Augustus in 476 to the spread of the European Renaissance in the 16th century) as an era of technological stagnation and economic backwardness (Gies & Gies, 1997: 1). Gibbon was correct that the demise of the Roman state and its economic infrastructure led to a steep decline in the cultural and economic capacities of Western Europe. [Get a quote from Gibbon.] As the architectural and engineering marvels of the Roman Empire crumbled and the intellectual legacy of antiquity became the preserve of the church, the population of Western Europe went into steep decline following a series of wars, plagues and famines in the 6th century. And yet, between the 10th and the 14th century, Western Europe enjoyed three centuries of unprecedented economic growth and expansion during which its economic system and its relationship to nature was transformed. By the end of the 13th century, medieval Europeans were beneficiaries of a revolution in agricultural methods which reclaimed large tracts of land from the forest and sea, increased the intensity of agricultural production, and led to a significant growth in the population of Western Europe. This epoch of feudal expansion also encouraged a process of mechanization which produced decidedly more mechanized equipment and greater access to exosomatic sources of energy than any other human society that If iad hitherto existed (Gimpel, 1976). As Terry Reynolds, a leading historian of watermill technology argued, “if there was a single key element distinguishing western European technology from the technologies of Islam, Byzantium, India, or even China after around 1200, it was the West's extensive commitment to and use of water power” (Reynolds, 1983: 5).

Under feudalism, a militarized class of landlords were able to extract a surplus through the appropriation of the labor of peasants forced to labor on their lands. Unlike the more centralized tributary empires in China, the Indian subcontinent, and the Middle East, political sovereignty in Western Europe was highly fragmented as a result of the century long disintegration of the Roman Empire under repeated waves of barbarian invasion and the consistent pattern of ongoing military conflict that followed. The key institutions of the European feudal system were recognizable by the time of Charlemagne's coronation in 800 AD, but the real epoch of feudal dynamism only arrived with the expansionary movement towards colonizing the forests and “wastelands” of Europe from about 1000 to 1300 AD. This process saw the loosening of lordly control over the direct producers, increased class differentiation within the peasantry, and the deployment of technologies which increased labor productivity.

The improved effective capture of solar energy through crop rotation and improvements upon energy conversion systems such as horse harnessing technologies and the water mill were a central part of this process of feudal expansion (White, 1962; Munro, 2002; Gimpel, 1976). The technological shifts and the increased labour productivity that these improvements made possible were derived from the changing class dynamics resulting from feudal expansion and the shift made by lords during this time from reliance upon direct labor services to monetary and monopoly rents from the peasantry. The great expansion of water mill technology over these centuries was shaped by the class interests of the lords to increase their revenues by enforcing lordly monopolies over milling and cloth fulling and went hand-in-hand with the suppression of peasant hand mill technology. This class-led dynamic led to such an abundance of water mills in feudal Europe that the historian Joel Mokyr claimed that "medieval Europe was perhaps the first society to build an economy on nonhuman power" (Munro, 2002: 224).

Medieval Europe's energetic revolution was so profound that even though it ultimately culminated in an extraordinarily severe ecological crisis that led to the death of up to one half of the population in the 14th century, it laid the groundwork for much of the technological infrastructure which would be later appropriated in England's 18th century industrial revolution – an industrial revolution which was, for the majority of its first century, powered by water mills. In the feudal transformation of energy relationships we can see the development of technology to deal with the pressures of class conflict arising from stagnant or declining agricultural yields and the growth of an increasingly significant metabolic rift threatening the continued appropriation of the "free gifts of nature" – in sum, the interaction of a specific mode of production with thermodynamic processes over historical time.

The limits to feudal expansion became clear once the system had expanded over its available land mass. The negative aspects of the "medieval agrarian revolution" made themselves apparent through declining yields which were unable to keep up with rising population levels. Europe lacked the ability – at this time – to overcome shortages of food, minerals, and cheap labor through the exploitation of its periphery or the intensification of endogenous productive processes. The traumatic ecological crisis of the 14th century which led to the death of nearly half of Europe's population through famine and plague is important to study because it showcases the limits of intensive forms of non-fossil fuelled economic growth. But the crisis of European feudalism was also of world historical significance because it forced both ruling elites and oppressed peasants in Europe to attempt a variety of different strategies to resolve this impasse, a process which led to several centuries of intense military conflict and peasant revolt. Ultimately, a trio of initiatives emerged as attempts to resolve the crisis – the Iberian led voyages of "discovery" and conquest in the Americas and along the Western coast of Africa, the development of the absolutist state to overcome the parcellized sovereignty of feudalism, and in England, the development of a system of agrarian capitalism which in creating a new agricultural revolution and overturning feudal social relationships, made the 18th-century Industrial Revolution both necessary and possible.

AFTER THE ROMAN COLLAPSE

With the final collapse of the Western Roman Empire in 476 A.D., Western Europe entered an epoch of economic decline that has been dubbed by historians as "the dark ages." During this time, all the indicators of civilized life – levels of urbanization, the production of cultural artifacts, literacy, trade, infrastructure building such as roads, etc. – precipitously declined. The reasons for this collapse are multifaceted. Some historians have tended to give greater weight to internal factors such as declining agricultural output, internal class struggles and the military conflict inherent in dynastic succession. Others have suggested that the primary factors were external to the Roman empire, and are explained by the vigour and military power of successive waves of barbarian invasions. [mention some sources here.]

In any case, the collapse of the Western Roman Empire was not a straightforward affair. Many of the Germanic tribes that eventually overthrew Rome had themselves undergone increased class stratification and Romanization simply by virtue of existing on the margins of the Roman Empire (Mann, 1986). Developments to their own productive capacity increased the numbers and military prowess of barbarian societies, and when they eventually overran Rome's European borders they were able to come to an accommodation with Roman aristocratic elites. The Germanic tribes were forced into conflict with Rome by pressure from Hunnic nomads who gained their military successes from a new technology of energy conversion that was put to military use. Renowned as skilled horseman, and able to raise the vast herds of horses required for their military conquest on the grasslands of the steepe, the Huns became a military superpower by equipping their fast moving cavalry with asymmetric compound bows capable of generating significantly greater range and hitting power than the bows used by their rivals (Heather, 2006: 154-158). The devastating military success of the highly mobile Hunnic mounted archers drove the Alans, Goths, Burgundians and the Suevi westward from the Hungarian plains and across the Danube and into the Roman Empire in the fourth and fifth century.

These migrating Gothic barbarians bled the Roman Empire dry as they ravaged the countryside and occupied key outposts of the Empire. In the fifth century, Rome's military might and its ability to generate surpluses from its provinces was terminally weakened by the Vandal invasion of North Africa, the capture of Roman provinces in the Iberian Peninsula by the Visigoths, and by Hunnic military victories in the Balkans (Heather, 2002). In the wake of the collapse of the Western Roman Empire, a new kind of ruling elite within the Germanic kingdoms evolved, and in a 'cataclysmic collision and fusion' with the institutions of the decaying Roman Empire, eventually produced the feudal mode of production in Europe (Bloch, 1973: 142). A new ruling class arose through the interpenetration of the conquered Roman aristocracy by the ruling elite of the Germanic tribes, and within a few generations "a Germanic aristocracy was consolidated on the land, with a dependent peasantry beneath it" (Anderson, 1974: 115). Many elements of the Roman civilian bureaucracy as well as its juridical structures were maintained within these new barbarian states, while the Germanic ruling elite converted to Christianity – thereby preserving the major source of ideological continuity with the achievements of antiquity. However, while the Germanic invasions produced an “aristocracy endowed with larger estates than ever before” and “populated the countryside with durable village communities and clumps of small peasant property” it was not yet capable of organizing “these disparate elements of the rural economy of the dark ages into a new and coherent mode of production” (Anderson, 1974: 124).

Plagues and famines swept across Western Europe throughout the last half of the sixth century, ravishing urban populations in towns and villages (Duby, 1974: 12). However, the steep fall in population levels in the Europe of the sixth century was not simply due to the plague. Population in the Roman Empire had been declining since the reign of Marcus Aurelius (121-180 A.D.) and labor shortages had become acute by the fifth century, thereby encouraging barbarian incursions into the thinly populated Roman territories of Western Europe (Munro, 2002: 228; see also Heather, 2006). The economic historian Georges Duby estimated that by the sixth century C.E. the population of Europe per square kilometer had sunk to about 5.5 in Gaul, 2.0 in England, 2.2 in Germany, and that only 3.5 to 4% of present-day Germany consisted of arable land (Duby, 1974: 13). By the ninth century, Western Europe’s population had reached its nadir, and with about 40 million people, contained less than half of the inhabitants who lived there at the height of the Roman Empire (Monro, 2002: 228).

These population levels were an expression of the extremely low productive capacity of Western European agriculture under its barbarian overlords. The use of metal tools was rare, and largely limited to the edging of hand tools used to reap crops or to hoe the earth. It appears that most plows were not assembled by specialists, but were rather built by individual peasants on their homestead and thus most likely lacked iron and would have been impossible to use on the heavier, more fertile soils of Western Europe (Duby, 1974: 15). Roman cities were emptied of their population as the ruling elite took up life on their manors and the urban artisans and city-dwellers dispersed once the flow of agricultural surplus stopped arriving in the cities.

For several centuries following the Roman collapse, agricultural production continued to limp along a trajectory defined by the ideological infrastructure of the Christian church and the patterns of Mediterranean agriculture inherited from Rome (Stevens, 1966: 92-124; Parrain, 1966: 126-179). The church required a continued cultivation of wheat and grapes as important symbols of human sustenance in its religious rites, and it therefore prioritized the growth of these crops on its extensive land holdings (Duby, 1974: 18). The agricultural productivity of manorial grain production was very low, rarely producing a seed yield higher than 2.0 to 1. As Duby notes, the available evidence suggests a “hazy but probably reliable picture of widespread cereal cultivation, extensive rather than intensive, very demanding of manpower, yet woefully inadequate to provide nourishment… Europeans of those times lived permanently with the spectre of starvation” (Duby, 1974: 28-29).

But the extension of such forms of agriculture were difficult in the early medieval era, as these forms of cultivation were easily destroyed by the marauding war bands endemic to Western Europe during this time (Pearson, 1997: 26). Consequently, the old Roman distinction between the *saltus* (pastoral lands set aside for animals) and the *ager* (arable land for the growing of crops and vines) began to fade as an increasing source of nutrition in the post-Roman dark ages came from direct products from the wilderness – venison, boar, fish, and other wild game. As Duby noted, "the fall of Rome was thus made manifest in the restoration of both the village types and farming practices that had formerly been features not of the *ager* but of the *saltus*, and of a culture designed not for cultivation but for the exploitation of the natural wilderness" (Duby, 1974: 21). Cultivation increasingly reverted to pre-Roman forms of slash and burn agriculture rather than the two field crop rotation system practiced by the Romans in the Mediterranean, and the return to hunting-gathering methods became an integral part of early medieval subsistence for those not ensconced within the manorial system.

The development of the manorial system alongside the earlier practices of swidden agriculture and hunting and gathering raises interesting questions about the relationship of class societies to thermodynamic processes. 'Slash and burn' agriculture as practiced by early Germanic societies was highly productive in mature deciduous forests, and could readily achieve cereal yields of 20:1 – dramatically higher than those of the agriculture associated with both manorial and later open field agricultural systems (Cooter, 1978: 472). The productivity of swidden agriculture stemmed from the fact that:

> Forest covers will have choked out most weeds, along with their reservoirs of dormant seeds, and will, by the same token, have starved out the pathogens associated with these weedy species. As a result, seed beds can be readily prepared with simple dibbles or hoes in clearings fashioned most economically by ringing the barks of well-spaced mature trees. Swiddening in climax forests would have been so economical of labor that it would seem that only some extraordinary inducements could have led to its abandonment (Cooter, 1978: 473).

Obviously, rising population pressures or other ecological factors could have overtaxed swidden agriculture located within climax forests, but given the vast tracts of primeval forest that remained available for 11th century colonists, it is unlikely that this was the case. It is likely that the shift to manorial and feudal systems of agriculture can be better explained as occurring through the use of armed force to make "more readily accessible what may have been a diminished total productivity for the use of the ruling elites" (Cooter, 1978: 475). The key point here is that even though swidden agriculture was a more thermodynamically efficient means of producing an agricultural surplus, the surplus produced under this relationship of labor to nature did not easily lend itself to appropriation by a feudal or manorial elite. Consequently, such cultivation was discouraged and viewed as infringing upon the manorial rights of the lords even though less than 5% of the land in the 6th century was to be found in arable production (Williams, 2000: 39). The manorial system was thus in comparative terms a very thermodynamically inefficient system for producing an ecological surplus, but the most effective means by which the new Germanic ruling class could monopolize that surplus and ensure that the direct producers which it controlled would continue to produce it.

In the three centuries following the collapse of the Western Roman Empire, no new territorial empires arose in Western Europe that were capable of incorporating localized manorial systems into a coherent whole. Instead, there was a steady and near continual state of warfare in which roving bands of warriors sought to pillage whatever resources were available. Like all emerging modes of production, in order to successfully expand, feudalism needed to transform the human relationship to nature in order to provide a firm ecological basis for extracting a rising level of surplus from its labouring class.

THE EMERGENCE OF FEUDALISM

As Perry Anderson has argued, the development of feudalism arose as a "historical synthesis" between "two dissolving anterior modes of production – primitive and ancient – [which] eventually produced the feudal order which spread throughout medieval Europe" (Anderson, 1974: 128). The Germanic barbarians broke onto the stage of history as they emerged from a system of communal ownership of property into a class stratified society led by warrior kings, while the Roman empire was slowly decomposing under the weight of its own contradictions and the pressure of external invasions. Anderson suggested that the development of vassalage arose through the fusion of forms of aristocratic retinue which existed in both societies. The manor arose from the Gallo-Roman *fundus* or *villa* consisting of "huge, self-contained estates tilled by dependent peasant *coloni*, delivering produce in kind to their magnate landowners" (Anderson, 1974: 130). Germanic traditions contributed to the "communal enclaves of the medieval village" while the legacy of Roman law and the heritage of the classical Christian church were significant in the development of both juridical and state structures that lasted beyond the initial Germanic conquest. The church preserved literacy, and the monastic orders led in the development of some of the most important technological developments of the early medieval era. As Anderson argues, the church functioned as an important vessel which was

> sufficiently apart from the classical institutions of antiquity and yet moulded within them, and so capable of escaping the general wreckage to transmit the mysterious messages of the past to the less advanced future.... No other dynamic transition from one mode of production to another reveals the same splay in superstructural development: equally, none other contains a comparable spanning institution (Anderson, 1974: 136-137).

Some three centuries after the collapse of the Western Empire, Frankish warriors belonging to the Carolingian dynasty succeeded in establishing a new territorial state which incorporated most of the former European possessions of the Western Roman

Empire by fusing new military tactics with the ideological and organizational support of the Christian church. The Carolingian family produced four generations of highly effective military-political leadership: Pippin of Herstal (635-714), Charles Martel (686-741), Pippin the short (751-768) and his brother Carloman (706-754), and Charlemagne (742-814) who ruled from 768 to 814. Martel famously defeated the invading Muslim army of Abdul Rahman Al Ghafiqi at the battle of Poitiers in 732 and pioneered military tactics that met with consistent success ([Source?]). Martel's grandson Charlemagne further consolidated the Carolingian empire by not only successfully waging war on the Saxons, Frisians, Avars, Slavs, Lombards and the Arab emirs of the Iberian Peninsula, but by combining his military force with the ideological and organizational infrastructures of the Christian church (Pirenne, 1958: 62-66; also see Clark, 1969). In 800 A.D. Charlemagne was granted the title of the Emperor of the Western Roman Empire by the Pope and established the Holy Roman Empire which held sway over practically the whole of Christendom.

One of the novelties of Charlemagne's rule was that he fused his political organization with that of the papacy, and in a context of near total illiteracy, he gathered together church intellectuals to create centres of higher learning. A large reason for this was no doubt Charlemagne's recognition that despite the fact that he lived in an era in which "practically no layperson, from kings and emperors downwards, could read or write" (Clark, 1969: 28) literacy could be an effective tool for governing a far-flung empire and that collaboration with church intellectuals could provide ideological support for his rule.[41]

In a political sense, the feudal order of the Carolingian state depended upon a system of *vassalage* (personal homage) and *benifice* (the granting of land) which produced a class of *vassi dominici*, or direct vassals to the Emperor who were the nucleus of the Carolingian army (Anderson, 1974: 139). As Pirenne noted, "the vassal, who originally was only a servant, thus became a soldier whose livelihood was assured by the possession of landed property" (Pirenne, 1958: 55). The eventual result of this process was "the emergence of the 'fief', as a delegated grant of land, vested with juridical and political powers, in exchange for military service" in the yearly campaigns waged by the Emperor (Anderson, 1974: 140). The land itself was worked by peasant serfs whose labor, beyond that required to ensure their subsistence and reproduction was transferred to the lord in the form of direct labor services on the Lord's demesne or rent in kind or in money acquired from production on the family holding (Hilton, 1980: 14).

The essential institutions of feudalism were thus in place by the time of the death of Charlemagne (Anderson, 1974: 141). Charlemagne's Empire crumbled due to infighting amongst his successors and ongoing external attacks from Viking, Saracen and Magyar invaders, but the increasingly generalized serfdom of the peasant population and the power of local lords provided the preconditions for the growth of feudalism. As Anderson put it, "the entrenchment of local counts and landowners in the provinces, through the nascent fief system, and the consolidation of their manorial estates and lordships over the peasantry, proved to be the bedrock of the feudalism that slowly solidified across Europe" in the two centuries following Charlemagne's death (Anderson, 1974: 142). However, the economic basis for the Carolingian empire remained weak, having little in the way of monetary circulation, and tending to develop economically in autarchic ways with a very low yield from agriculture (Pirenne, 1958; Anderson, 1974: 141).

FEUDAL ACHIEVEMENTS AND ADVANCES

By the year 1000, the invading Vikings, Muslims and Magyars had largely been defeated or integrated within European polities, and feudal Europe underwent a process of rapid economic growth which lasted until the middle of the 14th century. This growth was significant because it not only saw an expansion in the total amount of land that was cultivated, but it also witnessed a much more intensive use of energy resources and the properties of the soil. The productivity of agriculture was increased through the adoption of new techniques and technologies that were more ecologically suited to the heavier soils of Western Europe than those systems Mediterranean agriculture used by the Romans. These new innovations included not only the mechanism of the heavy plow, but the increased use of horses rather than oxen in agriculture which came with improved methods of horse harnessing and shoeing, increased use of iron as a result of the development of new metallurgical technologies, and the increasing use of wind and water power to mechanize milling and to improve a range of industrial processes (Gimpel, 1976; Gies & Gies, 1994).

The increasing productivity of agriculture made possible a rapid growth in population which coincided with an expansion in the amount of arable land in Europe – as land was reclaimed from the sea in the low countries and a movement of internal colonization saw entirely new lands wrested from the wilderness. Between 650 and 1350 European population increased six fold, a level which after the 14th century demographic collapse was not surpassed for 200 years (Williams, 2000: 37). The rising population and the temporary elimination of military conflict between rival Christian principalities in Europe also laid the basis for a series of military crusades aimed at "liberating" Jerusalem and Palestine from the control of Islam and acquiring plunder through warfare.[42]

During this time, significant scientific and technological developments were made in both the field of warfare (the development of gunpowder and its use in siege warfare), transportation (the successful development of sea vessels able to make the connection between the Italian city states with the wool exporting and cloth producing areas of England and Flanders) and architecture (reflected in the building of the massive Gothic-style cathedrals). There also occurred a revival of trade and an increasing circulation of metallic coinage as well as the development of new financial instruments which facilitated long-distance trade. The adoption of the padded horse collar quadrupled the amount of traction horses were able to provide and led to their wider use in agriculture and transportation (Langdon, 1986). Similarly, the replacement of the undershot water wheel of antiquity with the overshot water wheel technology widely diffused in the Middle Ages more than doubled the power that could be produced from running water while requiring only about one quarter as much water, thereby making it possible to build waterwheels near much slower moving bodies of water (Munro, 2008: 232).

During these 300 years of feudal expansion, "in every branch of life – action, philosophy, organization, technology – there was an extraordinary outpouring of energy, and intensification of existence" (Clark, 1969: 36). The changing nature of medieval art and architecture were characteristic of this new era of expansion. As Clark noted, one need look no further than the great cathedrals of the medieval epoch to find "the evidence of this heroic energy, this confidence, this strength of will and intellect…" which

> has the style and rhythmic assurance of the greatest epoch of art. The skill and dramatic invention that had been confined to small portable objects – goldsmith work or ivory carving – suddenly appear on a monumental scale. These changes imply a new social and intellectual background. They imply wealth, stability, technical skill and, above all, the confidence necessary to push through a long-term project (Clark, 1969: 36-37).

As intricately designed as these cathedrals were, the sheer volume of stone that was quarried and transported to build them between 1050 and 1350 was astounding. During these three centuries, more stone was quarried in the building of 80 cathedrals, 500 large churches and tens of thousands of parish churches in France then was quarried over the three thousand year reign of the Egyptian pharaohs (Gimpel, 1984: 1). And as Duby reminds us, the incredible achievement of the urban cathedrals was closely related to the medieval agricultural revolution since the church

> …relied on the nearby countryside for the major factor in its growth, and it was the efforts of countless pioneers, clearers of land, planters of vinestocks, diggers of ditches, and builders of dikes, all flushed with the successes of a flourishing agriculture, that brought cathedral art to its fulfillment. The towers of Laon rose against a backdrop of new harvests and young vineyards; the image of the oxen used in plowing, carved in stone, crowned those towers; vineshoots appeared on the capitals of all the cathedrals…. The cathedral was the fruit of the system of manor lords – in other words, of the peasants' labor (Duby, quoted in Mazoyer & Roudart, 2006: 259).

THE CLASS DYNAMICS OF FEUDALISM

The reasons for the dynamic growth of Western feudalism during this era are not immediately obvious especially given the very low levels of agricultural productivity in the early medieval era. A variety of different hypotheses have been proposed to explain the rapid economic growth from 1000 to 1300 AD and subsequent decline of feudal Europe in the 14th century. Some historians, conscious of the ecological limits of early medieval farming and the relative lack of technological dynamism on the largely autarkic manors, have suggested that changing demographic factors can explain this dynamic (Postan; Ladurie; Williams, 2000). Others, like Pirenne have suggested that feudal expansion arose as a result of the reemergence of trade routes and commerce which re-emerged after having been cut off by Islamic expansion in the Mediterranean and Viking raids along the northern coasts of Europe (Pirenne, 1958). Another perspective, that of Lynn White and Jean Gimpel among others, argued for the importance of technological developments and changes in cultural assumptions associated with Christianity in paving the way for rapid economic growth (White, 1962; Gimpel; Gies & Gies, also see Hall, 1998).

In contrast, historians from a variety of Marxist perspectives have suggested that it was the underlying class relations of feudal society which proved foundational in determining the way in which demographic, technological and commercial factors influenced European economic expansion. In particular Robert Brenner insisted that it was the “property relations” or “surplus extraction relations” of a particular class structure that were determinative in imposing “rather strict limits and possibilities” on the trajectory of social development (Brenner, 1976: 31). Brenner described his perspective as follows:

> Class structure, as I wish here to use the term, has two analytically distinct, but historically unified aspects. First, the relations of the direct producers to one another, to their tools and to the land in the immediate process of production - what has been called the "labour process" or the "social forces of production.” Secondly, the inherently conflictive relations of property - always guaranteed directly or indirectly, in the last analysis, by force - by which an unpaid-for part of the product is extracted from the direct producers by a class of non-producers - which might be called the "property relationship" or the "surplus extraction relationship" (Brenner, 1976: 31).

Of the two forms of class structure that Brenner identified, the analysis in his famous essay “Agrarian Class Structure and Economic Development in Preindustrial Europe” which went on to launch the so-called “Brenner debate” on the transition from feudalism to capitalism, was largely focused on the latter aspect of class structure – the extraction of surplus by the feudal elite from the peasantry, and the resistance by peasants to that process. In this framework Brenner posited that the different outcomes of peasant struggle following the economic and demographic crisis of the 14th century were central in determining what strategies could be pursued by landlords (Brenner, 1976). In a nutshell, Brenner’s argument posited that in both Britain and France, peasant struggles of the 14th century were successful in destroying serfdom and led to the emergence of a free peasant class which was no longer required to labor on the demenses of their lords. In Britain, the landed elite responded to this success by turning to a strategy of enclosing and leasing out land to richer peasants and yeoman, and this led to the evolution of agrarian capitalism. In France on the other hand, the success of peasants in holding onto their land led to the rise of the absolutist state which taxed the peasantry as a whole and overcame the regional power of the aristocracy (Wood, 2002).

My analysis does not quarrel with Brenner's focus on the determinative importance of class relations, but it does point out Brenner's failure to adequately examine the first aspect of the class structure he identifies – the relations of direct producers to each other, to their tools, and to the land in the process of production. This aspect of class structure requires an examination of the metabolic relationship between human beings and nature since the question of technological development and the capacity for labor to appropriate an ecological surplus is of central relevance to the stability and evolution of particular social formations and their class structures. Brenner did not investigate the ways in which the primary producers in feudal society – the peasants – were able to use particular technologies to better convert energy and extract low entropy resources from their surroundings and how this dynamic expressed an attempt to fulfill their own class interests. Instead, Brenner put a much greater emphasis in examining the second aspect of the class structure he identified – the ways in which surplus was directly appropriated from the primary producers and how this dynamic shaped class struggle and state formation. Brenner is not alone among social historians in glossing over the metabolic relationships within feudal society. But in order to get an accurate sense of how feudalism developed and what its limitations were, we must look at the internal dynamics responsible for its growth and development, as well as consider the larger biophysical and ecological context in which it emerged (Moore, 2003).

While class relations shape which kind of technological innovations can be adopted, the dynamism of feudalism during the 11th to the 13th century clearly had a basis in an intensification of the capture and effective use of energy. What is fascinating about this process is that it was not governed by the straightforward advance of technology as White or Gimpel might assert, or in the exploitation of market opportunities as Pirenne and other proponents of the commercialization thesis might propose. Instead, the class relations of feudalism hampered the rational growth of the forces of production due to the way in which lords extracted surplus from the peasantry. When that social relationship changed and economic surplus began to be extracted from the peasantry in new ways, technological innovations which increased feudal society's capture and use of energy were given new space to grow and reproduce themselves. To expand upon this argument requires understanding both the economic laws of motion of feudalism and the ecological context in which both the class that produced the social surplus and the class which appropriated it operated upon.

Put simply, the economic – and ecological – dynamics of European feudalism centred around the extraction of a surplus produced by labouring peasants by a landed ruling class. Peasants were juridically bound to a particular lord and were required to pay rent to their lord in addition to producing the means for their own subsistence by growing food on land which they and their family had customary rights to use. As Marx noted, the most basic form in which this rent could be payed was through 'labour rent,' i.e. a juridical requirement that the peasant would cultivate soil that he had customary usage of for part of the week and work on the lands of the feudal lord for the remainder of the week. The amount of labour appropriated by the lord in excess of the time allotted for the peasant to reproduce the conditions of life for himself and his family constituted the amount of surplus value extracted by the lord, since "in this case rent and surplus-value are identical" (Marx, 1984: 790; also see Dobb, 1963: 35).

Marx understood the ecological aspect of this class relationship, pointing out that the "natural conditions or limits of rent," – i.e. the surplus value appropriated by the feudal lords – was determined by the relationship between the labor power of the direct producer and "the natural conditions of his labor, above all the soil cultivated by him," conditions which must be productive enough to allow for the reproduction of peasant life and the creation of a surplus which could be appropriated by the lord (Marx, 1984: 792). Therefore, the overall solidity and coherence of the feudal mode of production in Western Europe relied upon the metabolic relationship of peasant labor to nature, and the ability of the labour-nature relationship to produce a greater energetic return than was invested in it. As Marx noted,

> Should labour-power be minute, and the natural conditions of labour scanty, then the surplus-labour is small, but in such a case so are the wants of the producers on the one hand and the relative number of exploiters of surplus-labour on the other, and finally so is the surplus-product, whereby this barely productive surplus-labour is realized for those few exploiting landowners (Marx, 1984: 792).

As long as the productivity of this labor-nature relationship increased, peasants and lords were struggling over who would get what share of an increasing economic surplus. If however, the conditions of this labor-nature relationship deteriorated, there would be less of a surplus available to the lords and the peasants would not be able to reproduce their own conditions of life, much less a surplus for their lordly exploiters. As we shall see, it was exactly this dynamic, one which was simultaneously a relationship between classes and between labor and nature, which both produced the dynamism of feudalism and ensured its collapse in the 14th century.

Marx perceptively pointed out that the phenomenon of labor rent in conditions of feudalism allowed for gradual increases in peasant productivity. Because the amount of time that peasants had to labor on the demense was fixed by custom as a way of ensuring social stability, peasants had the option of improving the productivity of their labor during the times that they were not required to work on the Lord's demense. If for example, peasants were required to perform two days of labor on the Lords lands a week,

> …the productivity of the remaining days of the week, which are at the disposal of the direct producer himself, is a variable magnitude, which must develop in the course of his experience,

> just as the new wants he acquires, and just as the expansion of the market for his product and the increasing assurance with which he disposes of this portion of his labour-power will spur him on to a greater exertion of his labour-power, whereby it should not be forgotten that the employment of his labour-power is by no means confined to agriculture, but includes rural home industry. The possibility is here presented for definite economic development taking place… (Marx, 1984: 794).

Marx argued that the form of rent – the means by which surplus value was extracted from the direct producers – evolved from labour-rent to rent in kind and then to a money rent as the feudal social formation grew and became increasingly complex. This process allowed for new possibilities of economic growth. When paying rent in kind, the peasant produced goods embodying a certain amount of labor time and paid his rent by transferring these products to the landlord. Such a form of rent encouraged peasants to adopt agricultural methods which increased productivity, for if a peasant was able to produce a greater amount of grain with less labour, he could discharge his obligations to his lord with less effort (Marx, 1984: 795). In time, money rents also developed which required peasants to produce commodities for sale on the market in order to meet the payment required by their lords. This did not mean the development of a fully monetized market however, since peasants continued to produce the greater part of their means of subsistence themselves outside of market relationships. In order for money rent to develop, there had to be "a considerable development of commerce, of urban industry, of commodity-production in general, and thereby of money circulation," but the existence of money rent does not preclude the continuation of 'more primitive' forms of labor rent such as the *corvée* (Marx, 1984: 797). In addition to the direct payment of rent in these various ways, feudal lords also subjected the peasantry to a wide range of different taxes, tithes and fines, as a means of extracting even more surplus value.

What distinguished the extraction of surplus-value under feudalism from the extraction of surplus-value under capitalism is that under capitalism the economic relationship between producer and appropriator of surplus occurs within a formally equal relationship between buyers and sellers in a marketplace. Workers "freely" sell their labor power – a unique commodity which has the notable capability of creating more value than is required to reproduce it – and capitalists use this characteristic of labor power to make a profit. In contrast, under feudalism, the extraction of surplus value occurs under directly "political" conditions of compulsion. The peasant is legally required to pay rent to his Lord, and should he refuse, the military might of the well armed aristocracy and their retinues will strike him down, while on ideological plane the church will condemn him to everlasting damnation (Hilton, 1990: 50-52).

While the exploitative social relationship between peasants and lords endured over the *longue durée* of European feudalism, the feudal system was not a unitary whole. As Marx surmised from his assessment of the internal dynamics arising from the different ways in which feudal rent was extracted, there were internal dynamics to the system which encouraged its growth and development. Marc Bloch, one of the first 20th century historians to analyze the social relations of feudalism, distinguished between what he called the "two ages of feudalism." In the first of these ages – stretching from the collapse of the Roman Empire to the beginning of the 11th century – agricultural production was low, travel was difficult, trade and monetary circulation were weak, urbanized communities were small, and waged labor was insignificant (Bloch, 1961: 61-69 and Dobb, 1963: 36-37). By contrast, what Bloch terms the "second feudal age" was marked by rapid economic expansion, an increased use of money as labor rents and rents in kind were transformed into money rents, a rapid growth in population, the growth of commerce, and the colonization of hitherto under-utilized territories within Europe such as the Iberian plateau, the marshy lowlands of present-day Holland, Belgium and the Netherlands, and the vast plains east of the Elbe (Bloch, 1961: 69-71).

Following the work of Anderson and Brenner, George Comninel has suggested that what Bloch saw as a periodization of feudalism could be more accurately defined as a distinction between a manorial mode of production (extending from the declining years of the Roman empire to the disintegration of the Carolingian state) and the development of feudalism proper with the usurpation of kingly authority by regional nobles ensconced in castles unassailable by external military force (Comninel, 2003: 14; see also Aurell, 2006: 32). Further developing Brenner's analysis of the second form of class structure, Comninel argued that the key change between these modes of production occurred with a transformation of the social form of lordship. Under both manorialism and feudalism proper, peasants were exploited by their lords. What changed was the kind of control that the lordly class held over those who lived in its domains. Under manorialism, the lords governed the lives of the peasants on their lands, but had no juridical power over the freemen who lived in adjacent communities. The King exerted a kind of "public" political power and enjoyed the powers of royal command. As Comninel noted,

> The king held the power to call free men together for war, and to lead them; and not only to call them into his own court, but into the local assemblies which adjudicated crimes, levied taxes, and prepared for war. The king held, in short, the powers to tax, to decree, to command, and to punish. These powers were together known as the royal *bannus*, or the ban – a term which has come down to us in many forms through the rich associations it took on in the period of the feudal parcellisation of sovereignty (Comninel, 2003: 17).

In the decades around the year 1000, these powers were appropriated by local and regional lords who, aided by the defences of their castles, usurped the King's power to command, punish and tax and thereby created a new form of territorial lordship. This resulted in what Comninel termed an "epochal transformation in the character of the relations between state and society." In France where this transformation first developed,

> this transformation of merely manorial lordship into the parcellised sovereignty of seigneurie marked the beginning of a new epoch in

> class relationships, the onset of feudalism proper. In addition to the imposition of new forms of duties, levies, and obligations, the new context of social relations led to the transformation of the whole existing structure of dependency and surplus appropriation. The characteristic unit of French lordship became, not the estate as such, but the *seigneurie*: a jurisdiction, a collection of territorial rights, centred upon an estate held as a fief (Comninel, 2003: 18).

The shift in social relations that Comninel identified at the beginning of the 11th century led to a change in the class structure governing the peasant's relationship to the land and thereby the human metabolic relationship with nature. In gaining the full exercise of sovereign power, local lords sought to maintain and extend their powers by increasing the number of peasants working on their lands and increasing the surplus they could extract from them. One strategy to do this could come from increasing the labor requirements of peasants on the demenses of the lords. While such strategies did guarantee an increase in surplus going to the lords, the productivity of such forced labor was low and peasant resistance often minimized the effectiveness of such accumulation strategies (Dobb, 1963: 56). An alternative approach was to encourage peasants to cultivate unused lands of the seigneurie or new territory which had come into the lord's hands through the consolidation of this new form of territorial lordship. These lands existed primarily in the form of primeval forest or undeveloped "wasteland."

Such a move played into the class interests of peasants because it loosened lordly control while also helping to overcome the fragmentation of peasant landholdings through partible inheritance. It also benefited lords by bringing into productive use an area of land which had previously provided no revenue. In order to encourage peasants to undertake the strenuous labor required to clear these new lands, lords increasingly released peasants from onerous fines and duties, lightened or removed labor requirements on the demense by replacing them with rents in kind or later, as trade and monetary circulation picked up, in money rents (Hilton, 1980: 17). As Gottlieb noted:

> From the eleventh to the fourteenth centuries, within the feudal mode of production, a distinct pattern of development is visible: a movement away from a system of production and exchange based on extra-economic coercion and forced labor within local, self-sufficient and consumption-oriented economic units and traditional communally used/owned lands - and towards forms of production geared to exchange, increases in wage labor, the pursuit of trade and profit, strictly defined alienable private property in land, and an increasingly complex local and regional division of labor. These developments were accompanied by dramatic improvements in agricultural technique and large population increase (Gottlieb, ________)

This dynamic led to the emergence of a "kulak" class of well-to-do peasants who after accumulating some capital through participation within local markets practiced more efficient forms of cultivation and enlarged their property by leasing additional land and hiring their poorer neighbours to work that land (Dobb, 1963: 60; Hilton, 1990: 61). With the transition from labor rent to money rent, peasants were now free to put all of their energies into working on their own holdings, a dynamic which encouraged increased productivity. In addition to the changes occurring at a local level within peasant society, the lords were also constantly on the lookout to recruit new tenants to cultivate empty lands. Lords would often hire agents to recruit peasant labor and were even forced to compete with other lords in attempting to secure such labor. In many cases lords asserted land, allowing free peasants to clear forested land in return for paying fines, taxes, and rents in kind or in money.

However, one of the key factors to keep in mind is that the lords had very little involvement in the production process. The peasants were essentially autonomous in regards to their development of the productive forces, and the noble class played no role in managing the agrarian economy or in contributing to its productive capacity. (Hilton, 1978: 10). Lacking an entrepreneurial bent, the aristocratic ruling class was entirely parasitical on the peasant population. An increase of the surplus going to the lordly class simply meant greater spending on conspicuous consumption, more weapons for war, and did not lead to an improvement in methods of production on the land. Agriculture was the base of society, but the expenditures of the lordly class on warfare was almost entirely unproductive and did not give rise to any new economic processes. Furthermore:

> The profits of merchant capital, even though some might be spent in the purchase of lordships and feudal landed property, were certainly not invested in such a way as to improve agricultural production. Nor was there any significant investment in industrial production, largely because this was organized on the basis of the family enterprise which was as impenetrable by merchant capital as the peasant family enterprise was impenetrable by the feudal landowner. Mercantile profits remained almost entirely in the sphere of circulation (Hilton, 1978: 14).

The shift to new lands and the loosening of lordly control over the peasantry enabled peasants to increase their agricultural productivity without the same fear of having their increased production arbitrarily confiscated by the Lords. By the 12th and 13th centuries more economically successful peasants were able to purchase enfranchisement from their lords with cash payments and although still subject to taxation and fines were juridically free (Hilton, 1980: 17). In this way, the peasantry, especially the middle and upper layers of the peasantry, gained both the incentive and the capacity to undertake what could be termed a “medieval agricultural revolution” based upon new and more efficient ways of converting solar energy into food and raw materials.

It is also important to mention that the church and specific religious orders also played an important role in encouraging the European process of expansion into previously uncultivated lands. In part, the church’s interests stemmed from its ideological position that nature needed to be tamed and put under the dominion of man (White, 1967). But perhaps a more important reason for the involvement of the church in this process of internal colonialism were the possibilities that ecclesiastical authorities saw for increasing the size and power of their institutions, while simultaneously expanding the cultivated territory held by Christians. One way in which the church was directly involved in colonizing new lands was by setting up a system of *pariage* in which seigniorial rights were divided between the church and a secular Lord who donated undeveloped land and the rights to earn revenue from it to the church as an act of piety (Kroebner, 1966: 71-72). On these lands peasant colonists or *hospites* were organized in new villages based around small parcels of land on which they paid a yearly rent to the church. Juridically, these peasants were considered free and in many cases were expressly released from a wide range of taxes and military burdens as a means to encourage their productivity (Kroebner, 1966: 73-4).

Another decisive initiative that was led by the church came in the form of specific colonization missions into the wilds and wastelands of Europe where religious orders such as the Benedictines and the Cistercians built monasteries for the purposes of clearing land and draining swamps. One of the strengths of these monastic orders is that with their centralized structure, organizational capacity, and ideological interest in rationally expanding their own institutions, they were able to encourage economic development over a wide territory and to learn from the best practices that were developed. Without having to worry about the dissipation of estates through partible inheritance and encouraged by the permanent nature of their institution,

> the church was the only institution capable of carrying out accumulation on a large scale and diligently managing its possessions: in this society within a society, monasteries were the ideal sites for the rational exploitation of natural resources (Debeir et al., 1991: 85).

The contributions of the Cistercians to the medieval economy should not be underestimated. Their abbeys in England specialized in the production of sheep for export, with Fountains Abbey in Yorkshire having a flock of 18,000 sheep which due to careful breeding produced a high-quality wool that was much in demand. At the monastery in Les Dunes, monks converted over 25,000 acres of the Flemish coastline into rich and fertile soil, while the Cistercians of Eberbach exported some 53,000 gallons of wine a year (Gimpel, 1976: 46-48). The monasteries were also among the first places to see the widespread introduction of water mill technology to systematically increase the productivity of labor. As early as the beginning of the 12th century the Cistercians introduced

> …rationalization to an extreme point, since most of their monasteries – of which there were hundreds in Europe – were built to the same standard plan. This monastic community has often been cited as one of the very rare examples of a social group that initially adopted the technology not mainly to accumulate material goods or dominate other social groups, but to free time

> for other activities: 'the monks sought to spare themselves useless labor in order to have more time and energy for meditation and prayer.… They kept the gratifying work for themselves: copying, illuminating, engraving manuscripts. They left the less gratifying work to machines: grinding, pounding, sawing.' (Debeir et al., 1991: 85)

Valorizing physical labor and agricultural development, the Benedictines were excellent cultivators who revived the agricultural arts of the Romans and notably developed strains of fruit which could better handle the more northerly climate of Western Europe (Gies & Gies, 1994: 48). [Need to expand upon and develop the section on religious orders and technology a bit more.]

THE MEDIEVAL ENERGY REVOLUTION

The most significant transformation in the human metabolic relationship with nature under European feudalism came with the intensification of agricultural practices between the 11th and 14th centuries. Due to the exigencies of the Mediterranean climate, Roman agriculture was based upon a two field agricultural system which left a field fallow every other year and eschewed a spring or fall planting due to low levels of rainfall. In northwestern Europe, the three field crop rotation system was originally introduced on the large and well organized demesnes of the Carolingian crown and church across in the last centuries of the first millennium (Parain, 1966: 139).

The three field crop rotation worked by dividing a field into three equal parts. The first part of the field was planted in the autumn with crops such as winter wheat or rye. The second was planted in the spring with oats, barley or legumes such as peas, chickpeas, lentils, or beans. The third was allowed to recover from the previous season's planting and was left fallow (White, 1962: 71). The shift to a three field crop rotation represented an intensification of the agricultural process by about one third. By the 12th century, the use of the horse drawn harrow and roller, as well as the repeated plowing of the fallow in order to suppress weeds and plow under manure led to further gains in productivity (Mazoyer & Roudart, 2006: 263-265). This shift in agricultural methods was slowly diffused across Europe, but it significantly increased the amount of calories that could be produced from a given acre of land. In addition to increasing the productivity of the land, the three field rotation diversified the kinds of crops grown and not only lessened the chances of catastrophic crop failure but spread the labor of plowing, sowing and reaping more evenly throughout the year (White, 1962: 72).

Another important aspect of the technological advances in agriculture was the introduction of the heavy plow, an innovation of the Germanic barbarians which marked a significant departure from the scratch plow or *ard* that was used around the Mediterranean basin. Unlike the *ard*, the heavy plow did not require cross ploughing, and so fields became longer and rectangular in shape as opposed to the Roman crosshatched square pattern. The furrows produced by the heavy plow increased drainage on the fields, which was necessary given the much heavier clay soils of northern Europe. The heavy plow was a sophisticated mechanism which used a knife-like iron coulter to slice vertically into the sod, a horizontally mounted plowshare to sever the underlying root structure and a mould board to lift and turn over the turf. Attached to iron banded wheels, this heavy plow required a much greater amount of animal power – usually eight oxen – and was "an agricultural engine which substituted animal-power for human energy and time" to thereby increasing labor productivity (White, 1962 : 43; also see Williams, 2000: 38)

The shift to a three field rotation and the increasing use of the heavy plow was also connected to an intensification in the use of forms of animal power in agricultural work and transportation. Horses increasingly came to replace oxen as a means of providing mechanical energy for plowing, and while early agricultural treatises such as Walter of Henley's *Book of Husbandry* (c. 1280) promoted the agricultural virtues of oxen, peasants tended to purchase the cheapest animals they could acquire. These often tended to be elderly horses which were sold by the manors while they still had some value and which happened to be more versatile and useful than oxen, principally because when harnessed to carts could provide thousands with much greater access to markets (Holt, 1998: 118). As Holt pointed out, the increasing use of horses "was an example of a major innovation, then, which was achieved without the need for unusual investment on the part of innovators and which occurred within small-scale enterprise" (Holt: 1998, 118).

The key to this increased use of horse power was an important innovation in harnessing technology. In European antiquity, a throat and girth harness was used to yoke horses. This system put undue pressure on the animal's windpipe and jugular vein and made it very difficult for horses to pull heavy loads (Lefebvre des Noettes). In seeking to reduce the damage done to draught animals by this harnessing method, the Theodosian code of 438 A.D. limited the amount of weight a team of horses could pull to just under 500 kg. Because of inefficient horse harnessing, oxen, whose yoking system was much more efficient, were used for practically all forms of plowing and hauling, while horses were used to pull very light chariots for ceremonial purposes or as cavalry in warfare (Langdon, 1986: 8). The use of the padded horse collar, an invention which was likely diffused westward from China, placed the load-bearing weight on the horse's shoulders and chest and allowed horses to safely pull over 10 times the Theodosian limits. This represented a very real and significant increase in the amount of motive power that feudal society was able to extract from its draft animals, with some experts suggesting that by the end of the 11th century, 70% of the energy consumed in medieval England came from horses and oxen, with the remainder coming from mills and human motive force (Langdon, 1986: 20).

In addition to being able to plow faster than an ox, horses were also important for their usage in cartage. As Langdon notes,

> Practical experiments, for instance, indicate that when pulling

> equal loads a horse can do so at least 50% faster than an ox. In the Middle Ages an increase of half again in terms of earth turned or goods transported would have been an event of some moment for medieval farmers. Nor can it be argued that there was little outlet for this extra power. In particular, the upsurge in land clearance that characterized 12th and early 13th century Europe would have found this excess traction especially useful (Langdon, 1986: 21).

Horses thus began to replace oxen which had been the major source of animal power in European agriculture. However, unlike oxen which could simply graze on waste lands, horses needed to be fed oats which in turn encouraged the spread of crop rotation to provide grain for horses. The more effective harnessing of horses increased the range of overland travel, as well as the amount of power which could be achieved in using horses for plowing or the powering of mechanical devices such as mills. The size of villages grew as "even a slight increase in the distance which it was convenient to travel from the village to the farthest field greatly enlarged the total arable land which could be exploited from the village" (White, 1962: 68). As Duby noted, "countries where this took place witnessed an improvement in the preparation of the land and thus in its fertility, a reduction in the duration of the fallow, and a rise in return on seed sowing. The whole process marked the advent of a much more productive agrarian system" (quoted in Gimpel, 1976: 36). Precise computation of levels of agricultural productivity are notoriously hard to ascertain, but sources indicate that productivity increased significantly, from a yield of about 2.5 to about 4.0. In some ecologically favourable areas, extremely high yields from the cultivation of wheat approximated modern yields (Gimpel, 1976: 43).

The agricultural revolution of the Middle Ages thus necessitated the negotiation of a complex series of technological developments which took time to spread over the patchwork of agrarian communities within medieval Europe. The three field system and increasing use of animals required not only new buildings capable of housing increased numbers of animals in the winter months, but also improved methods of harvesting and transporting feed for animals confined to farm buildings during the winter. The development of the scythe was crucial in allowing for the more effective harvesting of hay, but required increased metal production to produce the blades. In order to return manure to the fields, cartage and harnessing methods also had to be improved, while transportation and adequate plowing required the shoeing of draft animals (Mazoyer & Roudart, 2006: 270). The end result was not only increased of productivity in agriculture, but also rising levels of investment in capital equipment which represented a big difference from the farms of the 10th century (Holt, 1998: 116). As Mayoyer and Roudart put it:

> One or two scythes, a cart, a plow, a harrow, a roller, and relatively large farm buildings to shelter the hay, litter, and increased numbers of livestock are, essentially, the working capital of the new farmer of the thirteenth century, not counting the small tools, sickles, hoes, and spades that from then on have working

> parts made of iron. All of that represents, in the end, ten times the value of the equipment, buildings, and livestock of its much smaller homologue of the tenth century, which hardly possessed more than an ard, a packsaddle, small tools, often entirely made of wood, a simple house for the farmer and family, and far fewer animals (Mazoyer & Roudart, 2006: 270).

THE WATER MILL

In addition to transformations within the agricultural sector which saw an increased capture of solar energy into chemical energy appropriable by humans, significant growth occurred in the human capacity to capture nonliving sources of energy such as wind and water power. There is very scarce evidence that water mills were used in the Roman Empire. While a few accounts do exist of such technology being used, most historians concur that with a ready supply of slave labor, "water mills remained scarce in the late Roman Empire, vertical wheels scarcer, the more efficient overshot type scarcer yet, and non-milling applications barely, if at all, existent" (Gies & Gies, 1997: 35). [There is some controversy about this. Need to look at more recent scholarship on this question.]

The progression of the waterwheel in Western Europe is startling. "From the end of the fifth century until 800 A.D., a few dozen for the entire West; from 800 to 1000 A.D., hundreds; in the 11th century, over 10,000 for the kingdom of France alone" (Robert Philip in Debeir et al, 1991: 75). Evidence of such growth is also reflected in England where the Domesday book commissioned in 1086 by William the Conqueror assessed 9250 manors holding a population of roughly 1.4 million people. Over the territories surveyed, 5624 water mills were recorded, and more than one third of the manors had one mill or more in operation (Gimpel, 1976: 12). The increase in mechanical power produced by these mills was quite significant. Debeir et al. conservatively estimate that an average mill had an output of 2 to 3 horse power, meaning that in the 11^{th} century, France was able to produce the equivalent of between 40,000 and 60,000 horse power through its milling technology. Given that human physical labour can produce at most 0.1 horse power, hydraulic power contributed the equivalent in energetic terms to the labour of one quarter of the adult population of France (Debeir, 1991: 76).

The rapid growth of water mills during these three centuries of rapid economic growth under feudalism can be explained by the fact that control of the water courses from which hydraulic power could be generated customarily belonged to the feudal lords and provided a lucrative source of income. As Carus-Wilson pointed out, lords claimed "the right to dispose of the watercourse as he pleased for fulling and dying, reserving it wholly to himself, or leasing it out, often as a monopoly, to others" (Carus-Wilson, 1941: 52). The increasing use of water power was also closely tied to the economic interests of the seigneurial elite. One of the most significant areas of revenue for feudal lords was the receipt of "mill dues" – a percentage of the grain that was brought in to be milled by peasants. Feudal lords had a monopoly on the water-powered mills that they required peasants to grind their grain at. As Bois argued "…the spread of this invention had transformed the medieval economy, not only by the release of labor-power it permitted, but also since it made the mill one of the cornerstones of the lord's exploitation of the peasant" (Bois, 1986: 227).

The income received by feudal lords for the monopolies over the mills, grape presses and ovens which their peasants were required to use was substantial. Bois estimates it at 1 bushel of grain out of every 16 that were milled, or a levy of about 6.25% – more than half the amount that peasants normally paid in tithe. As Hilton notes, "the sum total of these new aspects of feudal rent… considerably exceeded the previous landlord income which have been based on the yield from the demense and the rents from the holdings" (Hilton, 1980: 17). The estate survey of one manner of the Abbey of St. Germain-des-Pres received as much grain in milling proceeds from its peasantry as it did from agricultural production on the Lord's desmense (Gies & Gies, 1994: 49). Because of the greater size of the surplus produced and transferred under new forms of jurisdictional and monopoly profits, lordly incomes became increasingly realized in cash (Hilton, 1980: 18).

As new technology such as fulling mills came into existence, the Lords insisted that all cloth made on the manor be fulled by mechanized means and no longer at home, just as they sought to prohibit the use of hand mills to grind grain (Carus-Wilson, 1941: 53). One of the most famous examples of this battle over energy resources came in a conflict at the Abbey of St. Albans in England during the 13th and 14th centuries. At St. Albans, the local abbot insisted that the grinding of all corn and the fulling of all cloth had to take place at the manorial mills, and went so far as to confiscate the all peasant hand mills, which he used to pave his parlour floor (Hilton, 1990: 4). In 1274 a major demonstration was carried out by the people of St. Albans who sought to make their plight known to Queen Eleanor who was passing through the area. Not surprisingly, their case was lost in the king's court (Carus-Wilson, 1941: 53-54). But peasant memory of this injustice remained, and during the peasant rebellion of 1381 insurgent tenants tore up the paved surfaces within which their ancestors hand mills had been ensconced and distributed fragments of the stones as tokens of solidarity in the spirit of sharing the sacrament (Gies & Gies, 1994: 116). **[Need something on windmills**

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THE 14TH CENTURY CRISIS OF FEUDALISM

Despite the intensification of agricultural production and the more efficient tapping of energy resources such as the horse and water mill, the feudal boom of the 11th to 13th centuries culminated in ecological crisis and demographic collapse in the 14th century. Both the nature of the crisis, and the way in which different social classes responded to it were determined by the underlying economic laws of motion of the feudal mode of production. The central problem was that production relations in feudal Europe were not capable of overcoming the tendencies towards diminishing returns in agriculture, mining and forestry. As a result, the feudal mode of production entered into crisis, inaugurating a century of war, famine, and plague. As feudal Europe continued to consume its main energy supply – the forest – and as agriculture expanded onto increasingly marginal lands and depleted the fertility of better off lands, feudalism proved incapable of producing a self sustaining economic "take off" (Rostow, 1981).

The increased productivity of the three field rotation had allowed for tremendous demographic and cultural growth, but it was only ecologically sustainable in the short term. Because of the decrease in fallowing, the land required greater labor inputs through the spreading of manure and the use of repeated plowing to suppress weeds or to plow under nitrogen fixing crops as "green manure." However, the three field rotation inherently reduced the amount of land available for pasture (and thereby manuring) while it increased the amount of arable land under cultivation. The logical solution was to develop new pasturage through forest clearance, but given increasing population growth, these new pastures tended to become quickly converted to arable land, thereby repeating the whole process over again (Moore, 2003: 108-109). As Cooter noted:

> When pushed harder, open-field husbandry had the potential for bursts of increased productivity, measured either in increased acres under crop or even in rates of yield, but this only at the cost of a more rapid depletion of nutrient supplies from arable hinterlands. Such bursts could be sustained for varying periods of time, depending on the initial ecological status of the hinterlands and a host of technological and organizational factors affecting how efficiently the stepped-up nutrient flows were utilized (Cooter, 1978: 470).

Cooter estimated that such stepped-up production could be sustained for 50 to 100 years, but after that time, productivity would taper off as a consequence of the failure to maintain soil fertility. Not only were medieval farming techniques limited by the fragmented nature of peasant holdings and the difficulty of storing and transporting manure to far-flung fields without reliable power technology, but the social relations of feudalism helped to undermine ecological methods of farming. One example of this dynamic is the way in which many lords required that peasant's sheep be "folded" on the lords demesne overnight, thereby limiting the possible fertilization of peasant fields (Dobb, 1963: 43).

The fundamental problem was that medieval agriculture produced an ever-increasing metabolic rift and was unable to overcome the degradation of European topsoil through either technological innovation, large-scale imports of foreign grain or territorial expansion. The techniques of the medieval agricultural revolution had spread throughout Europe but as ecological conditions declined, the system became "increasingly unsuited, despite all technological or organizational palliatives, to sustain adequately the socioeconomic and demographic systems that had battened onto them" (Cooter, 1978:

471). We see here the predictable consequences of the extension of the metabolic rift, and the consequent depletion of the soil fertility on which feudal society relied upon for its raw materials and food supplies.

> The last reserves of newly reclaimed land were usually of poor quality, wet or thin soil that was more difficult to farm, and on which inferior crops such as oats were sown. The oldest lands under plough were, on the other hand, liable to age and decline from the very antiquity of their cultivation. The advance of cereal acreage, moreover, had frequently been achieved at the cost of a diminution of grazing-ground: animal husbandry consequently suffered, and with it the supply of manure for arable farming itself. Thus the very progress of medieval agriculture now incurred its own penalties. Clearance of forests and wastelands had not been accompanied by comparable care in conservation: there was little application of fertilizers at the best of times, so that the topsoil was often quickly exhausted; floods and dust-storms became more frequent (Anderson, 1978: 197-198).

The reaching of Europe's internal frontiers and the degradation of the soil coincided with a larger climatological shift to a colder and wetter climate. Termed the "Little Ice Age" this era began with much colder winters between 1303 and 1328 (Moore, 2007: 47). The weather was unusually warm with very dry summers between 1284 and 1311, but in the winter of 1309/10 the winter was so cold that shipping was disrupted from the Baltic Sea to the English Channel and the Thames River froze solid (Fagan, 2000: 28). In the spring of 1315 it began to rain across Europe and continued without stopping until the fall. Cold snaps in the winters of 1305/6 and 1322/23 produced devastating crop failures. The wetter climate and the more intensive use of land dramatically increased the erosion of the topsoil. In the 1340s, this erosion increased to an unprecedented degree, accelerating soil erosion at a rate 22 times the norm of the first millennium. In 1342 catastrophic levels of rainfall in western Germany caused more than 30% of soil erosion in the past 1500 years to occur in this year alone (Moore, 2007: 48).

> The conjuncture of unfavorable weather and agrarian recession produced more than increasingly severe and widespread famine. It set the stage for the Black Death, which would wipe out somewhere between one-third and one-half of Europe's population in the middle years of the fourteenth century. These conditions played out on two fronts. The agro-ecological crisis led to widespread malnourishment. And the weather itself would play a key role, in concert with feudalism's far-reaching environmental transformations, including deforestation, but also related centrally to urbanization and the grain trade on which the cities depended (Moore, 2007:48).

On the back of repeated crop failures and wide ranging famines, the Black death, a highly communicable and extremely deadly disease swept through Europe in 1347-48 and returned repeatedly over the next half-century.

The problem of stagnant technology producing diminishing returns was evident in other sectors of the medieval economy as well. Mining technology had not kept up with the increasing difficulty of finding high quality silver deposits. By the first half of the 14^{th} century, mining ceased to be practicable in the mining zones of central Europe, because there was no way of sinking deeper shafts or refining impurer ores.

> Silver-mining came almost to an end in the 14th century. In Goslar there were complaints of a rise in groundwater level; there was also trouble with water in the Bohemian mines. The recession had already begun in Austria as early as the 13th century. Mining activity in Deutschbrod ceased in 1321, in Freisach about 1350, and in Brandes (French Alps) about 1320. (Van Bath, "the agrarian history of Western Europe" quoted in Anderson, 1974: 199-200).[43]

The failure of medieval Europe to develop the necessary power technology to pump out its deepening mine shafts was only one part of the equation. The widespread dissemination of the overshot water wheel had produced a transformation in the way in which iron was worked and made possible the creation of more effective implements, but the limiting factor remained the availability of local wood supplies. Despite the technological innovations which had dramatically improved methods of iron working, 14^{th} century metallurgy still required over 100 cubic meters of wood to produce one ton of steel (Debeir et al., 1991: 80). Cities competed with forges for wood supplies and those urban areas which lacked adequate river transport to the hinterlands where wood was available were reliant upon horse-drawn carts which could only travel about 20 km a day. The problem in this pre-fossil fuel era is that the highly limited methods of transport threatened to undermine the economic and thermodynamic value of the goods being produced.

> Neither the urban concentrations, nor the proto-industrial concentrations, could draw the energy they consumed from production areas located beyond the radius of a few dozen kilometres: beyond that distance, transport itself threatened to absorb the energy surplus produced by agriculture or forests and represented an exorbitant share of the cost of commodities, even of luxury items (Debeir et al, 1991: 81).

In a political sense the crisis was manifested by the rolling back of European expansion: "The rally[ing] of the Moors in Granada, the expulsion of the crusaders from the Levant, the re-conquest of Constantinople by the Byzantines in 1261, the Mongol conquest of the Russian plain" (Wallerstein, 1974: 38-39).

ATTEMPTS TO RESOLVE THE CRISIS OF FEUDALISM

[This section is very rough and needs a lot more work. I'm going to come back to it once I finish chapter 5 as it would be very easy to go off on a lot of different tangents related to such a huge subject matter.

]Perry Anderson summarized some very important conclusions to be drawn from the crisis of European feudalism which are worth quoting at length.

> One of the most important conclusions yielded by an examination of the great crash of European feudalism is that – contrary to widely received beliefs among Marxists – the characteristic "figure" of a crisis in a mode of production is not one in which vigorous (economic) forces of production burst triumphantly through retrograde (social) relations of production, and promptly establish a higher productivity in society on the ruins. On the contrary, the forces of production typically tend to stall and recede within the existing relations of production; these then must themselves first be radically changed and reordered before new forces of production can be created and combined for a globally new mode of production. In other words, the relations of production generally change prior to the forces of production in an epoch of transition, and not vice versa. Thus the immediate aftermath of the crisis of Western feudalism was not any rapid release of new technology in either industry or agriculture; this was to occur only after a considerable interval.… The direct and decisive consequence [of the crisis of Western feudalism] was a pervasive social alteration of the Western countryside.… Far from the general crisis of the feudal mode of production worsening the condition of the direct producers in the countryside, it thus ended by ameliorating it and emancipating them. It proved, in fact, the turning-point in the dissolution of serfdom in the West (Anderson, 1978: 204).

[Expand on this.]

The catastrophic loss of nearly half of Europe's population in the black death fundamentally affected social relations between lords and peasants, making labor costs relatively more dear. As Moore points out, the Black death "signed feudalism's death warrant" and encouraged development towards a new kind of social system.

> A relatively high labor-land ratio reinforced seigneurial power by tending to reduce labor costs, increase aggregate value appropriated in the form of feudal rent, and as a result, augment revenues. Conversely, a relatively low labor to high land ratio tended to reduce the surplus derived from the land, raise real wages, and depress seigneurial revenues. By the mid-fifteenth century, rents in England, Germany, and Italy were 40 percent lower than a century earlier; wages for laborers were as much as 400 percent higher (Moore, 2003: 50).

While in some countries, particularly England, feudal lords responded to the demographic collapse by shifting to new forms of agriculture such as sheep rearing which require dramatically less in the way of labor inputs, many lords were also driven to attempt to increase the rate of exploitation in order to make up for demographic losses through the levying of new fines and attempts to increase peasant exploitation. Predictably, this intensification of exploitation encouraged peasants to fight back against their lords. The 14th and 15th centuries thus saw a dramatic growth in social upheavals and peasant wars. One of the effects of this intensification of class struggle in Western Europe was the ending of serfdom and the creation of a free peasantry.

The crisis of the 14th century took more than a century to play itself out. At its conclusion ruling class elites took a number of different initiatives in order to increase their revenues and maintain their class position. Immanuel Wallerstein and other world systems theorists argue that the voyages of discovery" launched from the Iberian Peninsula around the coast of the African continent and towards the "New World" of North and South America were one consequence of this crisis of feudalism. Seeking new possibilities for food production and raw materials, the Portuguese expanded into the Western Atlantic seeking protein from fish, opportunities to produce sugar with slave labor, and supplies of timber for the building of ships and houses in wood starved Portugal (Wallerstein, 1974: 44-45)

> Europe needed a larger land base to support the expansion of its economy, one which could compensate for the critical decline in seigniorial revenues and which could cut short the nascent and politically very violent class war which the crisis of feudalism implied. Europe needed many things: bullion, staples, proteins, means of preserving protein, foods, wood, materials to process textiles. And it needed a more tractable labor force. (Wallerstein, 1974: 51)

The European ruling class was able to find these things in its colonization of Africa and the Americas. Jason Moore, operating within the world systems framework pioneered by Wallerstein has made the provocative argument that capitalism itself emerged in the context of the creation of a new ways of relating to nature that emerged as feudal societies sought to overcome the ecological limits of their own metabolic relationship with nature. This argument holds, like Wallerstein, that dynamics of international trade and colonial plunder were constitutive of the very existence of capitalism, by providing the basis for a new strategy of accumulation based upon new ecological relationships. One of the most important ways in which are ecological dimensions were transformed was in the introduction of new foodstuffs from the Americas. As Gies & Gies noted,

> One resounding irony of Columbus's voyage is that the New World produced none of the traditional spices he sought but supplied a trove of entirely new foodstuffs for the European table: maize (corn), potatoes, chocolate, peanuts, tomatoes, pineapples, green beans, lima beans, red and green peppers, tapioca, vanilla, and the turkey. At the same time, America gained many European crops: wheat, barley, broad beans, chick-peas (garbanzo beans),

> sugarcane. Asia and Africa were brought into the general exchange, Asia receiving sweet pota- toes, pineapples, papaya melons, and chili peppers while giving America bananas, rice, and citrus fruits. Africa received maize, manioc, sweet potatoes, peanuts, and green beans, and sent to America yams, cowpeas, coconuts, coffee, and breadfruit (Gies & Gies, 1994: 284).

The second way that the crisis of feudalism was met was through the development of "absolutist" state structures. Anderson argued that these "recharged" models of feudalism where power was concentrated in a central authority rather than dispersed, saw new economic and political advances within the system, including both the development of far-flung colonial empires as well as more efficient ways of pumping surplus out of the peasantry at home. In distinction to Moore, Anderson makes the point that these absolutist societies were not in fact capitalist even though in many ways they laid the groundwork for the development of capitalism.

Both of these areas provide important opportunities for discussion and analysis, but we shall focus upon the historical materialist approach of the so-called "political Marxist" tendency represented by such theorists as Robert Brenner, Ellen Meiksins Wood, and George Comninel. These theorists hold that English landowners responded to the changed circumstances created by the Black death by developing a fundamentally new kind of land tenure system based upon the displacement of peasants from their customary holdings, and the renting out of lands to the class of yeoman or capitalist farmers. They argue that this dynamic took place because of the way in which class struggles between peasants and landlord played out following the demographic crisis of the 14th century, and that England was launched upon its path towards capitalism by these internal class dynamics and not by the development of international trade, colonial conquests, etc.

These insights concerning the tendency of forces of production to "stall and receed within the existing relations of production" are of obvious relevance to today's ecological crisis, but first we shall turn to look at the ways in which the development of agrarian capitalism in England gave rise to the development of a whole new mode of production and ecological relationship to nature.

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[1] The recent scholarship by Foster, Burkett, Clarke and others on Marx's notion of the "metabolic rift" is an important exception to this tendency, and is taken up in the second chapter of this dissertation.

[2] So profitable was the making of improvements to these engines that James Watt, who perfected Newcomen's engine in 1776, made his fortune by billing his clients based on the amount of coal that they saved by using his machinery instead of the less efficient Newcomen engines.

[3] The disparity between British and French coal consumption at this time was enormous. In 1815 it is estimated that Britain used some 22.6 million tons of coal while the French only consumed 882,000 tons (Wrigley, 1988: 29).

[4] Verri (who Marx cited in *Capital* Vol. 1) wrote that "all the phenomena of the universe, whether produced by the hand of man or indeed by the universal laws of physics, are not to be conceived of as acts of creation but solely as a reordering of matter. Composition and separation are the only elements... [in] the reproduction of value... and wealth, whether earth, air and water are turned into corn in the fields, or the secretions of an insect are turned into silk by the hand of man, or some small pieces of metal are arranged together to form a repeating watch." (Marx, 1990: 133)

[5] Marx notes in *Capital* Volume 1 that "When man engages in production, he can only proceed as nature does herself, i.e. he can only change the form of the materials" (Marx, 1990: 133)

[6] As Marvin Harris argues in *Cows, Pigs and Witches*, the Middle Eastern prohibition on the consumption of pork can best be explained by the ecologically destructive consequences of raising animals with such high water consumption needs in arid climates (Harris, ___).

[7] Georgescu-Roegen did not rule out the possibility that a fourth "Promethean revolution" might produce a significant breakthrough in allowing for the continued growth and development of industrial civilization, but he did not count on it (Gowdy & Mesner, 1999: 62).

[8] The German Marxist Elmar Altvater, is one exception to this tendency, as he expands on the work of Georgescu-Roegen in his 1991 book *The Future of the Market: an Essay on the Regulation of Money and Nature after the Collapse of 'Actually Existing Socialism' (Altvater, 1991)*.

[9] In 1987 Martinez-Alier wrote an influential history of the contributions made by social scientists to the study of energy flow. Martinez-Alier suggested that his book could be seen as the history of the precursors to Georgescu-Roegen's "conceptual overturn in economics," and suggested that a school of ecological economics "has objectively existed since the 1880s" (Martinez-Alier, 1987, 2-3).

[10] It is worth noting that Georgescu-Roegen was critical of Daly's notion of the steady state, arguing that "the crucial error consists in not seeing that not only growth, but also a zero-growth state, nay, even a declining state which does not converge toward annihilation, cannot exist forever in a finite environment" (Georgescu-Roegen, 1972: 23?).

[11] John Stuart Mill lived through the early stages of the Industrial Revolution, but his work was primarily a synthesizing of the work of the classical political economists rather than a development of his own original perspective.

[12] Of course it is worth keeping in mind that the development of capitalism and the small-scale and localized production mythologized by Smith, Locke and Jefferson came into being through brutal extra-economic processes of slavery, colonization and primitive accumulation and not by individual industry and

personal effort in a free and fair marketplace (Marx, 1993: 873-931; Harvey, 2005.)

[13] The Malthusian tradition from which Daly draws his inspiration long sought to limit fertility. Frederick Engels in his "Contributions to a Critique of Political Economy" in 1843 notes that the writer "Marcus" proposed the establishment of "a state institution for the painless killing of the children of the poor... whereby each working class family would be allowed to have 2 1/2 children, any excess being painlessly killed" (Engels, 1843).

[14] Following the collapse of the Soviet Union, Cuba lost its most important trading partner and access to subsidized fossil fuel resources. As a result, the economy went into a tailspin. The Cuban government responded with an innovative urban gardening program and made a transition to organic agriculture to make up for its loss of pesticides, fuel inputs, and synthetic fertilizers based on fossil fuel resources (Source).

[15] It is worth mentioning that the historical record shows the exact opposite of Hardin's hypothesis as the norm. Instead of a reckless degradation of the environment due to overgrazing, access and use of the commons was regulated by custom in the interest of the community as a whole. The profit maximizing behaviour of Hardin's profit maximizing herdsman was kept in check by community control. (Find source).

[16] John Bellamy Foster points out some of the ways in which Marxist thinkers such as such as Bebel, Kautsky, Luxembourg, Lenin, Bukharin, Vernadsky, and a number of lesser-known Marxists theorists contributed to Marxist ecological thinking, but he acknowledges that even this tradition was largely extinguished by the late 1940s (Foster, 2009: 153-156).

[17] need footnote here citing their work

[18] Marx is here making the very astute observation of the ways in which human labor has dramatically transformed, and indeed through its interaction with nature, co-evolved with the world around us. As Marx provocatively suggested, "the nature that preceded human history… no longer exists anywhere (except perhaps on a few Australian coral islands of recent origin)" (Marx, quoted in Foster, 2000: 1, but find original source).

[19] We will see in our next section on raw materials how Marx developed a theory of economic crisis based upon the tendency towards underproduction of this industrial agriculture in relation to the needs of industrial capitalism for vegetable and animal raw materials.

[20] Although Marx does not mention it, the tendency towards underproduction and the widely differentiated location of these essential resources can become a major flashpoint of struggle between different capitalist nations as the attempt to gain control of these valuable supplies of raw materials has been a central aspect of inter-imperialist rivalry.

[21] This distinction goes to James Anderson, a farmer and political economist who in 1777 made the argument that rent work to equalize the value of produce from lands of different quality, as "a premium for the privilege of cultivating soils that are more fertile than others," an approach that Malthus and Ricardo were later to replicate (Schumpeter, 1981: 265).

[22] It is worth noting that this consideration arose in light of the processes of colonization that European societies were engaged in in the Americas. In these regions – after the dispossession and genocide of the indigenous population – large tracts of fertile land lay available for the taking, and a major concern of political economy was how to ensure that waged workers would not simply desert their employer and take up independent farming themselves.

[23] As Marx wrote "Although this description of the process is approximately correct for the settlings of modern peoples, it is, firstly, inapplicable to developed capitalist production; and [secondly] equally false *if*

put forward as the *historical* course of events in the old Europe" (source?).

[24] For example, Marx talked about the progression of different kinds of rents under feudalism, from a labor rent, to a rent in kind, to a money rent.

[25] As Mill noted "this law may however be suspended, or temporarily controlled, by whatever adds to the general power of mankind over nature; and especially by any extension of their knowledge, and their consequent command, of the properties and powers of natural agents" (Mill, 1987: 188).

[26] Kautsky did refer to the term "metabolism" once, but only in reference to the internal dynamic of capital (Kautsky, 1988: 209).

[27] Even if production was shifted to maximize the appropriation of renewable flows of energy, fixed stocks of low entropy energy and materials are required to build the wind turbines, solar panels, battery systems, and electrical transmission infrastructure.

[28] As Georgescu-Roegen noted, "Perhaps the Earth can support even 45 billion people, but certainly not ad infinitum. We should therefore ask "how long can the Earth maintain a population of 45 billion people?" And if the answer is, say, 1000 years, we still have to ask "what will happen thereafter?" All this shows that even the concept of optimum population conceived as an ecologically determined coordinate has only an artificial value.… The population problem, stripped of all value considerations, concerns not the parochial maximum, but the maximum of life quantity that can be supported by man's natural dowry until its complete exhaustion.… Man's natural dowry, as we all know, consists of two essentially distinct elements: (1) the stock of low entropy on or within the globe, and (2) the flow of solar energy, which slowly but steadily diminishes in intensity with the entropic degradation of the sun" (Georgescu-Roegen, 1999: 20).

[29] As the Marxist scientist and historian Joseph Needham put it in his analysis of thermodynamic processes "the most highly organized social communities should be the most stable, perhaps the most long-lasting…. The most highly organized social communities should also be the least wasteful." (Needham, 1942: 375).

[30] As we noted in chapter 1, Georgescu Roegen defines a Promethean Revolution as one which has "the property of being self-sustaining as long as fuel supply continues" and thereby was "marked by a qualitative conversion of energy and produced an irreversible change in the relationship between humans and nature, causing profound alterations in natural ecosystems and human societies" (Mesner & Gowdy, 1999: 57-58).

[31] Harris makes the intriguing point that one of the factors that undermined the process of state formation in Papua New Guinea was the fact that unlike cereal grains, yams – the region's main staple – could only be stored for 3 or 4 months before they rotted. This meant that emerging leaders "could not manipulate people through dispensing food" and nor were they able to support a permanent military force. Furthermore, because most islanders got their main protein resources from nearby oceans and lagoons, they were never dependent on the emergence of "great providers" who in other societies were able to control access to food supplies and developed into the ruling class of the first proto-states (Harris, 1991: 110)

[32] (Flannery (1995), and Pyne (2001) suggest that this dynamic can be seen in Australia where most of the old growth forest was burnt down within a millennia of the arrival of the first humans (See Goudsblom, 2002: 29).

[33] Vaclav Smil estimates the energy densities of foodstuffs as follows: vegetables and fruits 0.8-2.5 MJ/kg; tubers and milk 2.5-5.0 MJ/kg; meats 5.0-12.0 MJ/kg; cereal and legume grains 12.0-15.0 MJ/kg; oils and animal fats 25.0-35.0 MJ/kg (Smil, 1994: 12).

[34] It is worth noting that even prior to this, many early Neolithic settlements, such as for example the famous Çatalhöyük site in Turkey were located on alluvial plains that were prone to flooding (Fairbairn, 2005).

[35] As Hyams notes, the Nile carries between 70 and 150 million tons of silt through its waters every year. By means of comparison, if during the 7000 years of Egyptian agriculture, the Nile had only deposited an average of 50 million tons of silt a year, this would still be more than 300 times the total amount of Europe's current topsoil (Hyams, 1976: 46).

[36] For reasons of space, we are limiting this discussion primarily to the emergence of civilization in Western Asia, and not discussing the development of agriculture in the Americans, India, Papua New Guinea or China.

[37] As Harris notes: "… the forests of Anatolia were reduced from 70 percent to 13 percent of total surface area between 5000 BC and the recent past. Only one-fourth of the former Caspian shorefront forest remains, one-half of the mountain humid forest, one-fifth to one-sixth of the oak in juniper forests of the Zagros, and one-twentieth of the Juniper forests of the Elburg and Khorassan ranges. The regions that suffered most were those taken over by pastoralists or former pastoralists" (Harris: 1991: 198).

[38] As Debeir et al point out, "…in 209 BC, after the conquest of Tarentum, which had allied with Carthage, 130,000 inhabitants of the city were sold; in 177 BC, after the suppression of a revolt in Sardinia, the sale of 80,000 Sards in Rome led to a collapse of the price of human chattels. In the same years, according to Strabo, 10,000 slaves - probably an exaggerated, albeit revealing, figure - transited every day through the port of Delos, which was granted the status of free port by the Roman Senate in 166 BC" (Debeir et al., 1991: 37).

[39] This effort to bind the primary producers tightly to the soil ended up laying the groundwork for the feudal mode of production which emerged after the fall of the Roman Empire.

[40] White makes a similar argument concerning the stagnation inherent in "the social system created by the new [fossil] fuel technology [which] came eventually to act as a brake upon further cultural advance" (387) although here his reasoning is much less clear, especially given the tremendous and continued growth of the capitalist system under its fossil fuel energy regime.

[41] One of the welcome side effects of Charlemagne's support for intellectual endeavors was the preservation of much of the knowledge and literature of antiquity. As Clark remarks, "with the help of an outstanding teacher and librarian named Alcuin of York, [Charlemagne] collected books and had them copied. People don't always realize that only three or four antique manuscripts of the Latin authors are still in existence: our whole knowledge of ancient literature is due to the collecting and copying that began under Charlemagne, and almost any classical text that survived until the eighth century has survived till today." (Clark, 1969: 30)

[42] As Anderson noted "the thrust of the feudal mode of production at its height produced the international crusading expeditions of 1000 to 1250. The three great prongs of this expansion were into the Baltic, the Iberian Peninsula, and the Levant. Brandenburg, Prussia and Finland were conquered and colonized by German and Swedish knights. The Moors were driven from the Tagus to the Sierra Granada; Portugal was cleared in toto and a new kingdom founded there. Palestine and Cyprus were seized from their Muslim rulers. The conquest of Constantinople itself, definitively breaking the remains of the old Eastern Empire, seemed to consummate and symbolize the triumphant vigour of Western feudalism" (Anderson, 1978, 196).

[43] It is worth noting that European silver mining made a major recovery in 1460 when new technological improvements quintupled silver production in central Europe by allowing for the development of previously marginal mines (Wallerstein, 1974: 41).