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A GUIDE TO STUDYING THE SOCIO-ECOLOGICAL TRANSITION IN EUROPEAN AGRICULTURE

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Abstract: This paper shows the potential of the Social Metabolism approach to study the industrialization of the agriculture. It provides information about the physical functioning of agrarian systems over time and their spatial differences. It also sheds light on how the industrialisation of agriculture occurred; in other words, how the Socio-Ecological Transition (SET) took place in agriculture. The paper begins defining the characteristic features of the Organic Agrarian Metabolism (OAM), the starting point of Sociecological Transition. The next section examines the main changes there been in agrarian metabolism until its complete industrialization. This analysis is enriched by the concept of the SET since, by showing the paths followed by industrialisation from a physical perspective, it establishes the research agenda or points out a series of issues that should be prioritised in research; it facilitates identification of the driving forces for change that interact between social and environmental factors; and it establishes special scales in which transition occurs and the relationship between them. The paper ends with the application of this conceptual fremework to teh First Wave of industrialization in European Agriculture during 19th century.

Key words: Social Metabolism; Socio-Ecological Transition; Preindustrial Agriculture; Industrialised Agriculture; Agricultural Change.

Resumen: El presente texto muestra la utilidad de la propuesta teórica y metodológica del metabolismo social para el estudio del proceso de industrialización de la agricultura. Constituye una guía para su estudio que incluye, primero, una definición precisa de metabolismo agrario como aquella parte del metabolismo social especializada en la producción de biomasa; en segundo lugar, la identificación de las principales fuerzas motoras de las transformaciones agrarias, combinando tanto factores de carácter económico como social y político; en tercer lugar, identifica los distintos niveles o escalas en que ocurre la transición socioecológica y, por último, establece las principales oleadas del cambio hacia un metabolismo agrario de naturaleza industrial. El texto termina con la aplicación de este esquema conceptual al caso de la agricultura europea durante el siglo XIX.

Palabras clave: Metabolismo Social; Transición Socioecológica; Agricultura preindustrial; Agricultura Industrializada; Cambio Agrario.

JEL: Q10, Q11, Q19, N53

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Summary

Introduction.

Analysing agrarian systems from the past by applying theories and methods of Social Metabolism is particularly useful in Agrarian History, but also in all disciplines involved in the study of agriculture. It provides information about the physical functioning of agrarian systems over time and their spatial differences. It also sheds light on how the industrialisation of agriculture occurred; in other words, how the Socio-Ecological Transition (SET) took place in agriculture. Following the approach taken by Fischer-Kowalski and Haberl (2007, 3), for the purposes of this study, socio-ecological transition is understood as a process of change from one state to another that is qualitatively different from the former, a process that is not linear and which can even be chaotic. Transition does not travel along previously trodden paths, and its change or direction cannot be controlled entirely; along the way there is space for spontaneity or the appearance of unpredictable phenomena (Holling, 2001).

Edgar Morin (2010) suggests that the necessary change towards a more sustainable world is a process of *metamorphosis*, a new qualitatively different socio-ecological order that must be built, however, on the existing foundations. By doing so, it distances itself from the eternal contradiction between reform and revolution, between evolution and rupture. The concepts of SET and *metamorphosis* complement each other well, allowing transition to be understood as a process by which the Social Metabolism changes its organic form, for example, to an industrial one. Metamorphosis admits hybrid forms, variable in their duration, diverse forms in which the metabolism is not entirely organic or industrial.

The analysis of agricultural industrialisation is enriched, therefore, by the concept of the SET since: a) by showing the paths followed by industrialisation from a physical perspective, it establishes the research agenda or points out a series of issues that should be prioritised in research; b) it enables the pace of the transition or metamorphosis to be studied, therefore, in close relationship with the social metabolism as a whole; c) it facilitates identification of the driving forces for change that interact between social and environmental factors; and d) it establishes special scales in which transition occurs and the relationship between them. This information is of great interest to project transition towards sustainable agrarian systems from an agro-ecological point of view.

1. The place held by the agrarian metabolism in the social metabolism.

The Social Metabolism is in reality a concept drawn from biology and transferred to the world of relations between society and nature (Martínez Alier and Schlupman, 1987; Fischer-Kowalsky and Haberl, 1998; González de Molina and Toledo, in print). Its metaphoric quality and essentially analytical dimension (non-normative) which is applied to socio-ecological relations on the basis of a unit or boundary defined by the researchers legitimates its transferral to the sphere of agriculture.

The Social Agrarian Metabolism or Agrarian Metabolism (hereinafter the SAM or AM) alludes to the exchange of energy and materials established by a society's agrarian sector with its environment. The AM, therefore, is considered to be the part of the Social Metabolism that specialises in the 'production' of biomass. Therefore, the boundary of the AM coincides with the concept of the agro-ecosystem in its broadest understanding, which includes not only farming activity *per se*, but also areas of land that are used for human benefit and, therefore, are subject to some kind of appropriation.

The use of the AM fits in best with the approach taken in Agrarian History. It enables both the start of the transition (under an organic metabolism) and the end of the transition (under an industrial metabolism) to be tackled with the same unit of analysis. The metabolic function of the AM is not just to provide biomass for human nourishment, but also raw materials for industry, fuel (in many cases), and medicinal substances and, no less importantly, environmental services.

Therefore, the AM is identified with the development of two basic tasks, closely related until now: a) the management of agro-ecosystems for the appropriation and 'production' of land biomass, generating a certain quantity of waste (Gliessman, 1997; 2002 Altieri, 1989; Guzmán Casado et al., 2000); and b) the provision of environmental services (Daily et al, 1997; De Groot et al., 2002; EEA, 2001; Pagiola et al., 2004). This requires the colonisation of certain ecosystems and the appropriation of part of their net primary productivity (HANPP). Therefore, an almost essential unity can be established between the AM and the footprint it makes on land ecosystems, which are appropriated and manipulated to produce biomass for human use.

This consideration of the agrarian metabolic process in turn requires the analysis of interactions it maintains with the SM as a whole. The transition from an organic agrarian metabolism to an industrial one cannot be understood without these interactions. For example, the energy change towards fossil fuels that took place in the 19th Century in Europe had a decisive impact on the transition. Furthermore, the different place occupied by the AM in the SM depending on whether it is an organic or industrial metabolism must also be taken into account. Its functions changed during the SET and that had an important influence on the configuration of the AM, changing from a supplier to a receiver of energy.

2. Characteristic features of the Organic Agrarian Metabolism (OAM).

The main characteristics of solar energy-based agrarian systems have already been described in several recent studies (Wrigley, 1988 and 1992; Sieferle, 1990; González de Molina, 2001; Krausmann, 2001 and 2004) and we are not going to repeat them here. However, I would like to point out a few essential features of their functioning. The appropriation and production of biomass was achieved through the management of agro-ecosystems, which aimed to imitate natural ecosystems as far as possible. This management necessarily interfered in the carbon, nitrogen and phosphorus cycles, in the hydrological cycle and the mechanisms of biotic regulation. It entailed an external contribution of energy that had to come from biological sources: human and animal labour, which in turn depended on the capacity of the agro-ecosystem to produce biomass (Altieri, 1989). The incorporation of energy was limited, therefore, by the amount of territory available and the type of converters, plants, which could best adapt to the environmental conditions. Agrarian societies, therefore, maintained a very strict dependence on their provision of land and its soil and climate conditions.

Ultimately, the fundamental source of energy was provided by the *domestic extraction of biomass.* The near impossibility of importing significant amounts of external energy into managed ecosystems[1] meant that internal and external demands had to be met using the available land. Therefore, farmers were obliged to adopt a strategy that combined different land uses in a complementary way. Croplands were allocated to

[1] The capacity to move people, animals and goods over medium and long distances was severely restricted. In relation to this question and its effects on trade, see Smil (1994, 131), Sieferle (2001) Martínez Alier, (2007), Hornborg (2007, 6).

producing food for human consumption or fibres and other raw materials of interest to humans. Pastureland was destined to producing food for animals and, finally, forestland to the production of fuel and construction materials, wood and timber. Certainly, these three major alternate uses of the land could be found alongside one another in the same farm, combining different crops and uses (agro-forestry systems, for example), but their feasibility depended on the soil and climate conditions of each ecosystem and on its productive capacity. In climates where primary production was depressed through the lack of rainfall or nutrients, the land cost of biomass production was higher than in areas where these factors abounded. In certain dry, semi-arid and arid regions, where water was scarce, the land uses could even compete with one another and be practically mutually exclusive, leading to a high consumption of land (González de Molina, 2002).

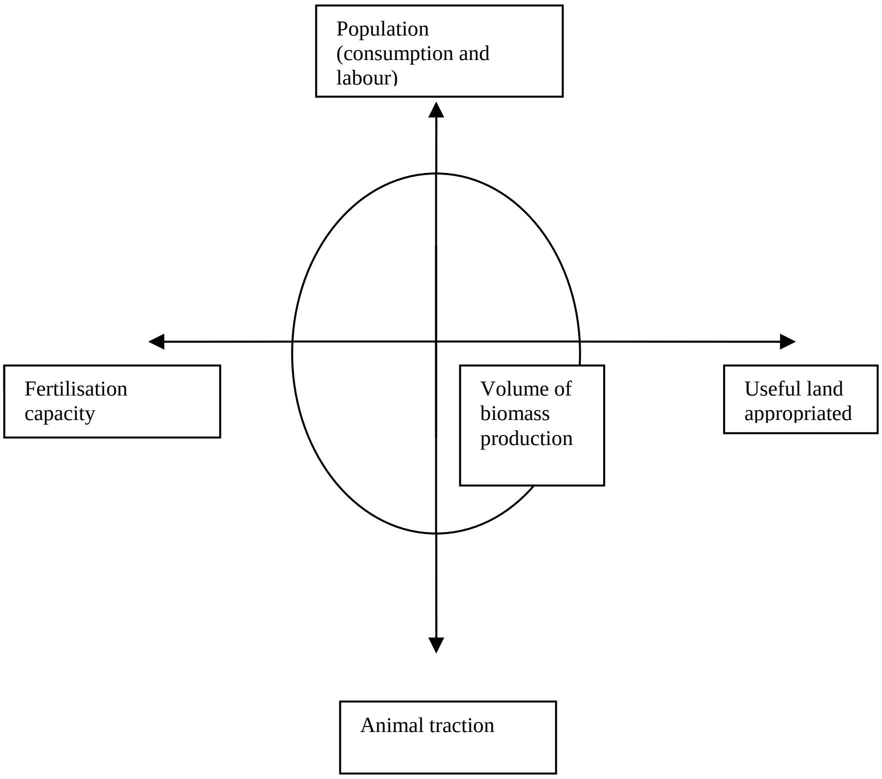
The distribution of land into *ager*, *saltus* and *silva* was compelled by another two kinds of reasons: on the one hand, the diversification of usage, in other words, spatial heterogeneity, was a way of imitating the dynamic of natural ecosystems and thereby achieve maximum sustainability (Gliessman, 1997, 304); and on the other hand, because the balance between different land uses became crucial to the attainment of socio-environmental stability, avoiding dangerous territorial imbalances that led to population shrinkage, the appropriation of other territories, emigration, etc. As explained elsewhere (Guzmán, González de Molina and Alonso, in print), the production of biomass entailed a territorial cost (*land cost*) that was determined not only by the amount of land required to produce it according its soil and climate characteristics (*land requirements*), but also by the layout of the territory or the specific combination of land uses (*land functionality*) which ensured its stability over time (in agro-ecosystems managed industrially, this balance is ‘replaced’ by ‘equivalent land’ thanks to the use of fossil fuels). The land cost reflected the size attained by the agrarian metabolism at each time and in each place.

These territorial servitudes reduced what is now understood by harvest, in other words the kilograms of, for example, grain that could be directly sold in the market or used to make bread. The replenishment of fertility compelled a certain amount of land to be destined to fallow or to feeding animals that could produce manure; working livestock had to graze on pasture, and when this was not sufficient, on grains taken from food supplies intended for human consumption; the by-products of cereals and leguminous crops were, in many agrarian cultures, an essential supplement to animal feed. In fact, the traditional varieties of these crops were selected with this function specifically in mind and, therefore, they offered harvest coefficients in which the ratio between straw and grain was strongly biased in favour of the former. These and other characteristics of traditional farming production explain why yields were lower than currently. Farmers were striving to optimise the net primary productivity of the system as a whole rather than the commercial part of a certain crop, in order to ensure that the system would function without causing environmental damage. Of the whole of the net primary production of appropriated ecosystems, including agro-ecosystems, only a percentage was dedicated to human consumption and an even lower part was aimed at the market.

This balance between the different land uses can also be seen on an aggregated scale. For example, at the start of the 19th Century, Austria used 40% of its total land for the provision of food, 10-15% for working animals and 30% for heating. Biomass for non-energy uses (for example, wood for construction) was produced on less than 10% of the land (Fischer-Kowalski, Haberl and Krausmann, 2007, 227-229). This study also establishes, as in the case of Santa Fe (González de Molina and Guzmán Casado, 2006), the maximum energy density that could be achieved in Austrian ecosystems at 50 GJ/ha/year. An increase above that figure was only feasible with an important subsidy of energy and materials from outside in the form of fertilisers and mechanical traction. The mean was situated at around 30 GJ/ha/year, which could sustain population densities of around 40 people/km^2, with a mean per capita in energy use of approximately 70 GJ/inhab/year.

Figure 1 represents the main variables involved in the creation of this ‘delicate’ balance. The level achieved by each or several of the four variables represented (population and level of endosomatic consumption, the installed power in terms of manual labour and animal traction, fertilisation capacity) determined the amount of biomass produced and/or appropriated, in other words, the size of the agrarian metabolism. It also functions inversely: the amount of biomass appropriated and/or produced determined the size of the population and its endo and exosomatic needs, maintaining the weak balance between livestock and fertilisation capacity. The territorial rigidity of the organic metabolism could only be overcome with the appropriation of more land or its products.

Figure 1: functional diagram of organic-based agrarian systems.



However, the expansion of appropriated land had physical as well as topographical limitations. As the farmed territory increased, so did the cost of transporting materials, livestock and manual labour. The increase in time lost in transit reduced the time available for farm work. Hence, the growth of farmed land could only be successful if the ratio of power invested in transport or during agrarian activities also increased. Both questions depended in turn on the availability of land (Giampietro, Bukkens and Pimentel, 1997, 142 and 151). Ultimately, an increase in the production of biomass for any purpose could only be achieved if a larger expanse of territory was farmed. But this solution had limits, not only derived from the similarly limited provision that each society had of this natural capital, but also because it required more work per land unit and that could also reduce the productivity of labour. Under such circumstances, there were few possibilities of having an economy in a ‘progressive state’, in other words, sustained economic growth (H. Daly, 1973; Sieferle, 2001).

In accordance with the above, the socio-ecological transition began when these ‘delicate balances’ were definitively broken; when the metabolic arrangement *was no longer sustainable*. Analysing the resilience of agrarian societies to cope with the ‘surprises’ or challenges that arise becomes an important issue. The general consensus seems to be that societies based on an organic metabolism had to cope with serious problems when the ratio between the population and the resources became unbalanced to the detriment of the latter. The four most critical environmental problems that compromised their sustainability were: i) deforestation (which had effects on the supply of fuel); ii) erosion and soil degradation (which affected and aggravated the land shortage); iii) the rupture of balances between different land uses (which relaxed the pressure of a growing population or its exosomatic consumption); and, above all, iii) the depletion of soil fertility (which prevented the production of biomass per land unit from growing and eventually reduced its productive capacity). All of these problems can be reduced to certain amounts of land, with provision being the crucial factor.

3. The SET in the AM: the metamorphosis of an Organic Agrarian Metabolism into an industrial one.

With the industrialisation of agriculture, the agrarian metabolism specialises preferably in the production of biomass, but not exclusively (it continues to provide raw materials), for the satisfaction of society’s endosomatic consumption. The agrarian sector is ‘expelled’ from the energy system and becomes a recipient of energy and materials from elsewhere. The nucleus of the agrarian metabolism is still Domestic Extraction (DE), but the Importation (I) of energy acquires a decisive importance.

The SET can be understood as the process of externalisation and peripheralisation of the basic functions fulfilled by the production of biomass in the reproduction of the organic social metabolism. From the centre to the periphery. From the soil to the subsoil. The social agrarian metabolism (SAM) went from being at the heart of the metabolic process to constituting an apparently marginal segment of the same thanks to the exploitation of fossil fuels. This metamorphosis, which occurred at a pace increasingly gathering speed, began in England, made the leap to continental Europe, expanded towards its peripheries and today is still spreading to every corner of the globe.

In effect, the production of biomass no longer provides the bulk of the energy that allows society to function. The domestic extraction of biomass represented between 95 and 100% of the energy consumption in organic metabolism societies, whereas in societies where the industrial metabolism has become the dominant way of organising relations with nature, biomass only produces between 10 and 30%. Furthermore, the energy balances show that it has changed from being a supplier to a demander of energy (Leach, 1976; Pimentel and Pimentel, 1979; Naredo and Campos, 1980, Carpintero and Naredo, 2006; Cussó et al., 2006; González de Molina and Guzmán Casado, 2006). Without the subsidy of external energy, a part of global agriculture could not function.

This major injection of energy and materials explains why yields per land unit have multiplied, offering the capability of feeding a population that has grown six-fold since the start of the 19th Century, giving rise to one of many paradoxes. According to Smil (2001, 256), the total area of farmed land in the world grew by a third during the 20th Century; however, because productivity has multiplied four-fold, the harvests obtained in this period increased six-fold. But as Smil himself acknowledges, this gain is partly due to the fact that the amount of energy used in farming has risen eight-fold.

It also and particularly explains the exponential growth registered in terms of the productivity of agrarian labour. The cases studied conducted for Austria by Krausmann et al. (2003) and for Santa Fe (González de Molina and Guzmán Casado, 2006) mostly concur that the industrialisation of the agrarian metabolism led to a spectacular increase in the productivity of labour, thanks to the mass use of new technologies and the mass entry of external energy. Interestingly, both cases, built on the same methodology albeit at a different scale, coincide that this increase caused yields to increase five-fold. For example, in Santa Fe, the energy imported between 1752 and 1997 multiplied 55-fold, from 3% of the direct input of energy to 29% in the latter year (Guzmán Casado and González de Molina, 2008)

Agrarian activities have changed their metabolic functionality. They constitute another input in the metabolism of materials and, although the market does not reward this task, they offer essential environmental services (carbon sinks, climate regulation, water purification, maintenance of certain levels of biodiversity, etc.) for the stability of the industrial metabolism. Perhaps for that reason they have tended to become degraded through the very industrialisation and commodification of agriculture (De Groot et al., 2002; Pagiola and Platais, 2002).

But perhaps the most decisive change, owing to its impact on the species itself, has been the change in diet. Rich countries increasingly consume more meat and livestock products such as milk and its derivatives, causing livestock numbers to grow to unsuspected levels. To feed these animals, land has been taken away from food grown for human consumption or part of it has been dedicated to growing feed to fatten them up. According to Krausmann et al. (2008, 471), the global appropriation of land biomass in the year 2000 reached 18,700 million tonnes of dry matter per year, 16% of the world's net primary production, of which 6,600 million were indirect flows. Of this amount, only 12% of the vegetable biomass went directly on human food; 58% was used to feed livestock; a further 20% as raw material for industry, and the remaining 10% continued to be used as fuel.

The importance acquired by importations of energy and materials have led the AM to become partially uncoupled from the agro-ecosystems that sustain it and its spatial configuration to become radically different, based on simplified landscapes, single-crops, the loss of spatial heterogeneity and biodiversity. Basic functions that in another time were fulfilled by the land (production of fuels, food for livestock, basic foodstuffs for the human diet, etc.) to which a fairly large portion of the same was dedicated, disappeared, giving rise to a specialist landscape, essentially and almost exclusively agricultural, peppered with constructions and areas used for urban-industrial properties (Agnoletti, 2006; Cussó et al. 2006; Tello et al., 2008; Guzmán Casado and González de Molina, 2006 and 2008).

4. The driving forces.

As with the social metabolism as a whole, changes in the metabolic relationship between agrarian societies and their environment (their dynamic) emerge from the relationship between *population* and *resources.* There are many factors that shape each of the two poles in this relationship and many variables that alter it.

<u>In terms of resources</u>:

1. Changes in the provision and quality of natural resources.

Changes in the quality and quantity of the environmental resources and functions offered by agro-ecosystems are determined by the dynamic of nature itself, a dynamic that has a long temporal dimension, but in which sudden changes are not excluded. Climate fluctuations and other unpredictable or surprising events have had a direct impact on the dynamic of the organic metabolism, creating more or less favourable conditions for agricultural, livestock and forestry activity and therefore increasing or decreasing the amount of land required to meet social needs, for example, the impact of the climate changes that took place in the 14th Century in Europe, related to the Little Ice Age and certain volcanic eruptions, which brought rainy autumns, cold springs and humid summers, flooding, etc. During that period, there were plagues of locusts, earthquakes and The Black Death. These disturbances significantly increased the price of basic grains, causing famines, increased mortality rates and a decrease in the population, and sparking a prolonged economic decline (Pfister, 1988; Reilly and Anderson, 1992). Something similar occurred with the "general crisis of the 17th Century" (Dearing et al., 2007, 242), which originated in climate disturbances that accumulated between 1470 and 1630 then again between 1688 and 1720. The climatic anomalies provoked between 1788 and 1794 by El Niño in Australia, India, the Caribbean, North Africa, Western Europe and the United States, had dramatic social and economic consequences, as documented by Richard Grove (2007).

Yet, the quantity and quality of goods and services offered by agro-ecosystems can also be modified by the interferences of the population itself (society), for example, the effects of depleted guano reserves in Peru in the 20th Century or the deforestation and subsequent shortage of wood in 18th Century England. Social responses can be aimed at adapting or 'overcoming' these limitations via technology or new land arrangements.

In terms of the population:

2. Population size and structure.

Metabolic change must take *population size* into account as a fundamental variable. Size is the most relevant albeit not the only factor that explains the scope of *endosomatic consumption* among the individuals who make up the population[2]. Size can be and in fact is modified by the levels of *exosomatic consumption* within the

[2] It would appear that this factor suffered noticeable variations since the start of the transition: changes in diet and the growing use of luxury consumer items, especially among the dominant classes, had an impact on aggregated demand and, consequently, on the size of the social metabolism (De Vries, 1994; Pomerantz, 2000), which at this time was essentially agrarian.

population. This consumption may or may not exceed the environment's capacity to sustain the population, thereby favouring changes in the organisation of the metabolism.

Both the size and the structure of the population in turn have a clear impact on the agrarian metabolism: they establish the maximum capacity ('installed power' we might say, using the simile normally applied to machinery) of the labour force that makes it function. Well into the 20th Century, when the mechanisation of key agricultural tasks had been firmly consolidated, there was (and still is in many parts of the planet) a strong link between population size and crop intensity (Boserup, 1967).

European societies had embarked on a new era of expansion in the 18th Century, having overcome the climate and environmental disturbances of the previous century (Grove, 2007; Pfister, 1988). In just under a century, the number of inhabitants doubled. Improvements in public health and hygiene reduced catastrophic mortality, practically chasing the plague from Europe and limiting the damage done by the still frequent epidemics of cholera, measles, typhus, etc. The improvement of harvests and market supply increased defences against many illnesses, leading to an overall reduction in mortality (Wrigley, 1985; Livi-bacci, 1999; Flandrin and Montanari, 2004).

3. Inequality as a change factor

Social inequality is expressed as a non-equitable allocation of goods and services among social groups or territories. A physical approach to this social maladjustment would translate into the unequal allocation of the flows of energy, materials, water and environmental services, as well as the recycling of waste or rubbish; in other words, of the systems of absorption offered by ecosystems. A social group can force the overexploitation of one or several resources if it accumulates and/or consumes a growing fraction of the energy and materials that are 'socially necessary' for a society to subsist.

An example can explain this more graphically: in feudal or tithe-based societies, based on an organic metabolism, the increase in rent compelled farmers to offer a larger part of their harvest or any other natural resource to the detriment of the amount available for self-consumption which usually pushed them towards the breaking of new lands, fishing, catching or hunting more, and to the extraction or gathering of higher volumes of products. The expansion of the agricultural boundary, if land was not available in abundance, led to the forced rupture of the balance in terms of different land uses and created a situation of instability in the social metabolism which could lead to over-farming or ecological collapse. Something similar happened with the extraction of wood and timber from woodlands and forests. In societies with an organic metabolism, given that production is a zero-sum game (Sieferle, 2001, 27), the higher the exosomatic consumption of the opulent or dominant classes, the lower the consumption among the rest of society, even affecting the endosomatic consumption of the latter. Ultimately, the social mechanisms of exploitation or forced transfer of income can reduce the biomass available to meet both the endo and exosomatic needs of the population or, put another way, they increase the aggregated consumption of the population and increase the demands made on land over and above the size of its population.

From an environmental perspective, social inequality therefore constitutes an ‘ecosystem pathology’, a permanent source of metabolic instability and a powerful stimulus for conflict and socio-environmental change. This perspective is fundamental in our analyses, since it takes the concept of equity to the terrain of its effects on sustainability (Guzmán et al., 2000, 102). There are numerous cases both throughout history and in the present day in which poverty and the inaccessibility of resources have led to environmental degradation, deforestation and the reclamation of forests, to cultivation on steep slopes, overgrazing or the use of agrochemicals, etc.

To analyse the impact of social inequality on the process of socio-ecological transition, a distinction must be drawn between at least two dimensions of equity: internal and external (Guzmán et al., 2000). From the perspective of the internal equity of agriculture, unequal distribution of resources creates pressure towards a greater productive endeavour. Furthermore, the unequal distribution of resources has historically constituted a permanent source of *conflict* that has been a powerful driving force for the historic evolution of societies. For example, liberal regimes increased social inequalities in Europe excessively and placed farmers in a very precarious position. The legal-political framework of the feudal or tithe-based system which guaranteed the existence of common goods and rights that attenuated poverty disappeared, pushing farmers towards a new relationship of a more mercantile and monetary nature.

Farmers sought to increase productivity per hectare through more intensive crops that would provide them with sufficient income to cover the payment of higher rents, to buy basic goods for subsistence (timber, wood, pasture, forest gathering, other foodstuffs not produced on their farm, clothes, etc.) many of which they could no longer obtain free from common goods or rights of which they had been stripped through the implementation of liberal regimes based on private ownership and the market. In a context in which even land had been the object of private appropriation, the fragmentation of farms and their decreasing size, often imposed by regimes of succession, obliged farming families to increase their productive effort and search for alternate sources of income in the labour market. In the 19th Century, the growth of the population and the markets, especially national ones, created favourable contexts for a rise in agrarian prices, especially for basic products (Grigg, 1992), which fostered strategies of productive intensification and set in motion an intense process of farming specialisation focused on the market.

The central importance of the lack of equity found in the agrarian sector gave rise to a new form of inequity that constituted the most powerful driver of productive intensification and the breaking-up of agro-ecosystems. We are talking here about the growing inequality generated firstly by national markets and then by the world market when it came to distributing revenue between the agrarian sector and the other productive sectors, through which the latter clearly benefitted, a phenomenon referred to here as *external inequity* (Guzmán et al., 2000).

The global profitability of agrarian activity, even though it was still linked to crops that were in higher demand and therefore more profitable, declined progressively from the early 20th Century onwards as a consequence of the unequal relationship of exchange between the agrarian sector and the industrial and service sectors (FAO, 2004). The terms of exchange for primary producers declined by over 1% per annum in the period 1948-86. Although the evolution between 1900 and 1998 was not uniform, but rather developed in stages, with two collapses in 1920 and 1984, the accumulative effect was a decline of 62% in the terms of exchange (Zanias, 2005; Eisenmenger, Ramos and Schandl, 2007a, 183). The economic policies implemented by Governments coincided in favouring this unequal exchange, through their endeavour to promote industrial development.

The loss of profitability fostered a new process of crop intensification with which farmers and large landowners attempted to diminish agrarian income. This guided the choice of crops and management techniques implemented by large and medium sized farmers, familiarised early on with the market, and represented another turn of the screw for productive specialisation. They also adopted technological improvements that, provided by a thriving chemical and mechanical industrial sector, allowed them to boost yields and productivity (Koning, 1994).

Far from recovering lost profitability, this process made farmers even more dependent on the market and new technologies, in other words on the agro-industrial complex as a whole, to achieve a minimum income threshold. This non-egalitarian relationship between the agrarian sector and the rest of the economy occurred mainly through the combination of two closely related phenomena: on the one hand, the constant fall in prices perceived in real terms by farmers, a trend that remained as a constant throughout practically the entire 20th Century (see, for example, part III of the FAO, 1995). On the other hand, the growing use of industrial inputs, which incorporated greater added value, and with which farmers attempted to increase their revenue in order to counter the fall in perceived prices, led them to incur increasingly onerous costs, ultimately reducing their net margin. In short, the deterioration in agrarian revenue created a favourable context for the rapid spread and mass use of agricultural inputs. The growing insufficiency of earnings became a powerful motor for agrarian intensification and for small farmers to engage with the market through the purchase of inputs.

Intensification and commodification were, therefore, two closely linked processes which spiralled once they had a grip on production. At one point in their development, they generated a demand for energy and materials from the agro-ecosystem that the latter could not fulfil, exceeding its capacity for sustainment and degrading its resources and environmental function. Environmental deterioration created a new obstacle to intensification which had to be overcome through new technological changes; technologies that required a more intensive use of energy and materials that eventually deteriorated the agro-system even more and spread environmental degradation to other territories.

Furthermore, the process of commodification undermined the “ecological rationality” (Toledo, 1993) of farmers who, in organic agricultures, were obliged to combine multiple land uses, facilitating the provision of environmental services. Their growing and often forced commodification (Badhuri, 1983; Berstein, 1986, 2001; Van der Ploeg, 1993) compelled farmer to find incentives in production for markets and, consequently, the production of non-commodifiable goods and environmental services ceased to be a priority in new agrarian management strategies (EEA, 2001).

But the relationship between population and resources can be altered, in turn, by a series of technological, economic, political and even ideological factors:

4. Technological change:

Technological change is a first order variable that modifies the terms of the relationship between population and resources up or down. A certain ecosystem or series of them can in theory, depending on the physical and biological characteristics, sustain a certain number of individuals with a given level of endo and exosomatic consumption, determining the specific size of its metabolism. However, certain technological solutions can increase the carrying capacity above its possibilities at the expense of increasing metabolic efficiency in the use of energy and available materials, for example, through the use of leguminous crops, fodder plants, enhanced seeds, chemical fertilisers and irrigation technologies. In arid and semi-arid climates, this solution was applied in order to significantly increase the productivity of the land.

5. Institutional change as a vector for metabolic change

Institutional change, understood as a series of norms and conventions that regulate the access, use and exchange of natural resources, was decisively important in the initiation and development of the socio-ecological transition in the countryside. For example, liberal revolutions firstly stimulated and then sanctioned the rupture of the balances that protected the organic metabolism. The social relations identified firstly with capitalism as a socioeconomic system but also and later with 'real socialism' constituted a powerful driving force for the transition. In general, all these institutional changes stimulated responses that tended firstly to specialise production, subsequently to increase yields per land unit, saving land, and finally substitute human labour with machinery and chemical means. As we have seen, the social inequalities introduced by the institutional change that accompanied the institution of liberal regimes throughout practically the whole of Europe compelled farmers to implement adaptation strategies that converged in the intensification of crops. Ultimately, there has been no SET without the material basis that made it possible, but also without an institutional change that impelled it.

6. Economic exchange as a vector in the metabolic change.

An agrarian metabolism can grow above its provision of resources if it is capable of securing the resources required for its functioning from outside its own environment. In this respect, *economic exchange* constitutes a very relevant factor to explain socio-environmental change. In reality, it is an instrument used to transfer energy and materials between different societies, which in turn consumes energy and materials and produces waste. A society can increase the carrying capacity of its territory by importing resources from other societies through economic exchange.

The creation of markets in agriculture was *also* determined by the need to overcome certain factors (water, traction and nutrients) that limited the growth of production. The commodification of production and the ‘emancipation’ of the limits imposed by the land provision of the agro-ecosystem (and the quality of its soil and climate) are closely linked: the market was the vehicle through which subsidies of energy and materials circulated, crucial for the maintenance of growth in agrarian production. Firstly, the sphere was the local district, then the province, and later became regional, national and finally international. Commodification gradually increased its spatial scales until it became, as it is today, a global phenomenon. But the market was also the vehicle that transmitted requirements and pressures from other territories, via prices, on local agro-ecosystems generating demands in excess of the real demands of their population.

The drive to obtain sufficient income to survive or to maximise profits or earnings constituted a powerful mechanism that, increasingly expressed in the market, pushed towards metabolic change in agriculture (Berstein, 1977, 1986; Harris, 1982; Marsden, 1991). In this respect, growth and the change from an agrarian metabolism to an industrial one would not have been possible without the importation of energy and materials from outside agro-ecosystems. This would not have been possible without market competition but also without improvements in transport. Innovation in transport must be considered an active element in the process of transition. The crisis at the end of the century, for example, or the expansion of chemical fertilisers can only offer an adequate explanation if this factor is taken into account.

7. Political-military relations between metabolisms

The importation of resources can be carried out 'peacefully' through economic exchange or it can be forced through the *political-military subjugation* of one State by another, for example. These two phenomena are often found in combination. In this respect, the decisions that emanate from the mechanisms of power and, in general, from the institutions created within each society to regulate social relations and also the use of resources and environmental services are undoubtedly important. We are referring here to the series of *stable power relations* (regulations and legal norms) or one-off relations (decisions), which aim to reproduce both the metabolism between nature and society and the forms in which it is organised and, therefore, the way in which energies and materials flow within it. Influenced by the other factors, this factor in turn has a decisive influence on them and on the dynamic of the social metabolism.

8. Ideas about nature.

Ideas about nature and the human perception derived from nature have a decisive influence on the shaping of the metabolism and trends towards change. The current ecological crisis would be incomprehensible without the change in ideas about the countryside that have taken place since the end of the 18th Century, which facilitated the move from biocentric anthropocentrism to self-referenced anthropocentrism within human beings themselves. Influenced by world views, it is particularly important to take account of the *development of knowledge*, especially scientific knowledge, on which capacity for technological innovation has usually depended in recent centuries and, therefore, largely the very configuration of the metabolic process. This is applied to the development of agronomic science and the dominant visions of agriculture; an example is the superiority of chemical fertiliser over organic ones (Garrabou et al, 2010)

9. Environmental conflict.

A socio-environmental approach to the functionality of conflict and the manifestations - particularly collective - that may arise from it (from social protest to warring conflicts) compels an analysis of the impact that conflict might have on the environment. For example, the defence of common woodlands carried out by many indigenous communities in Mexico or India over a fairly prolonged period of time, taking them out of the market and preventing felling, has had a positive impact from the perspective of their conservation, although that has not been an explicit aim in the protest. On the other side we might place the struggles of workers in rural Spain and Italy in the mid 20th Century which, within a framework of unquestioned capitalist competition, provoked an increase in labour costs that favoured the mechanisation of cereal harvests. In the same way, the protests that many European farmers carried out in the last few decades of that century demanding more reservoirs or river basin diversions, have provoked an increase in the expenditure of energy and materials and have increased the level of unsustainability.

In this respect, conflicts in which there are implicit or explicit motivations of change regarding the metabolic *status quo* are worth particular attention. These kinds of conflicts, which can have very different motivations and expressions, have been justly termed *environmental conflicts* (Soto, Herrera and González de Molina, in print). The resolution of said conflicts has historically been a source of modification or conservation in metabolic configurations (Cobo, Cruz and González de Molina, 1992; Marínez Alier, 1993; Guha and Martínez Alier, 1997; Sala, 1996; Ortega Santos, 2002). For example, the protection given by many European farming communities to natural resources against attempts at overexploitation on the part of timber companies, livestock companies or the State itself, has reduced the impact of these societies on nature. We could say, therefore, that environmental conflicts *can* increase or decrease the size and intensity of the metabolism, the flows of materials and energy; therefore, they can contribute to increasing or diminishing the levels of sustainability. They can, ultimately, accelerate or delay the socio-ecological transition in the countryside.

10. Chance

Finally, it must be admitted as a true hypothesis that chance played a role in the transition, or more precisely, uncertainty, a factor normally ignored by social sciences.

5. The scales of metabolic change.

The study of the SET in the countryside requires a bespoke analysis of the changes that occur at four different levels or scales but which are closely interlinked. The first of them is the *crop scale*: at this level, during the transition very important transformations occur that affect above all the genetic material, in other words, seeds. In this sphere, farmers have aimed to maximise the harvestable part of the plant and especially the part that offers the greatest commercial value or the livestock species or breed with the greatest economic yield. The result has been the progressive reduction of genetic biodiversity.

Levels of the socio-ecological transition in the agrarian metabolism			
Global		X	XX
Nation-State	X	XX	XXX
Community	XX	XXX	XXXX
Farming Estate	XX	XXX	XXXX
Crop	XX	XXX	XXXX
Wave	1st wave	2nd wave	3rd wave

The second level of analysis focuses on the farming estate. The SET has signified a marked trend towards the suppression of associations of crops and multi-crops, towards the simplification of rotations for their subsequent suppression and replacement with crop alternatives governed by market demands. From heterogeneity in terms of crops and plants and their layout, we have moved towards single crops, significantly reducing genetic, structural and functional diversity (Gliessman, 1997)

The third level of analysis corresponds to the *organisation of the agro-ecosystem*. In this case, during the transition, there has been a growing segregation in the uses of land and the loss of productive and functional synergies generated by agro-forestry and pastoral integration. The progressive trend towards productive specialisation has been an ever-increasing demand that has tended to impose specialist land uses in accordance with market demands and the aptitudes of the lands and the provision of natural resources. The result has been the loss of geodiversity and spatial heterogeneity. With this, flows of energy and materials, which tended to be local and closed (renewable) have become global and based on fossil fuels.

The fourth and last level refers to the ‘greater society’, in other words, to the nation-state, firstly, and to the different stages in the process of globalisation. The SET has favoured the integration of agro-ecosystems in an ‘agrarian metabolism’, a ‘constellation of metabolisms” (González de Molina and Toledo, in print) increasingly broader in their geographical scope. During the first wave of the SET process, the nation-state fostered food self-sufficiency and the formation of a national market. This encouraged the integration, still productively diversified, of agro-ecosystems, attempting to produce enough to cope with growing national demand. With the second wave of the SET, the first globalisation of agrarian markets took place, which boosted the specialisation of each country according to its comparative advantages, a process that intensified with the third wave and has culminated today with the constitution of a global agrarian market and a single global agri-food system, in which agro-ecosystems are integrated in a specialised way.

The SET in the countryside could be understood as a continual endeavour to increase the production of biomass to meet the endo and exosomatic demands of society. The increase in production has necessarily entailed an increase in its land cost, which has stimulated the introduction of technologies and changes in the management of agro-ecosystems aimed at countering such an increase.

Indeed, the increase in the volume of production, if grounded chiefly in domestic extraction, generates a quantitative and qualitative consumption of land that eventually exceeds the provisions of any agro-ecosystem. Starting in at least the late 19th Century, this increase was achieved by dedicating an increasingly higher percentage of photosynthetic production to marketable biomass, a process stimulated by the progression of the industrial metabolism. Depending on the location of each agro-ecosystem, this entailed the preferential or specialist dedication to agricultural production, livestock production and/or the production of commercial crops (raw materials for industry). Depending on the scale, the most significant changes were as follows:

1. At the scale of agro-ecosystems, this process brought with it the expansion of certain land uses over others and the rupture of previous ecosystem balances; a reflection in turn of an increasing trend towards specialisation. The most widespread phenomenon in Europe was, in this respect, the promotion of agricultural uses over others or ‘agriculturalisation’ (in other places it was livestock), a process that had limits and very significant consequences: the reduction of other land uses and the subsequent reduction in livestock numbers (or the increase in grain or artificial grass to feed increasing livestock numbers). The absolute reduction of the agro-ecosystems’ own fertilisation capacity was

the consequence in the case of agriculturalisation, the increase in demand for fertilisation was the effect of livestock specialisation.

2. The promotion of agricultural uses over others and productive specialisation provoked, at the level of the farming estate, the progressive simplification of rotations, reducing the presence of fallow and/or making the insertion of more commercial crops more frequent in rotations. If, at the scale of agro-ecosystems, this phenomenon provoked a progressive decline in the agro-ecosystems' capacity to replenish their fertility autonomously, at the scale of individual estates, it provoked a considerable increase in the relative demand for fertilisers.

3. At the scale of the individual crop, the trend was towards the selection and improvement of seeds with a view to increasingly concentrating photosynthates in the marketable part of the plants grown. This culminated with the introduction of hybrid, designer seeds. This process also exerted pressure, together with the factors described above, for a more frequent or intensive use of fertilisers. The consequences have been the abandonment of seed varieties that are best adapted to the soil and climate conditions and, as far as we know, with a lower demand for nutrients (Guzmán et. al., 2010). The same is true of woody plants, whose multifunctional use gradually gave way to the chiefly commercial use of their fruits. The case of the olive tree is paradigmatic: from a tree that produced wood, fodder and the skins and stones used to feed cattle, domestic lighting and edible oil, they are now used almost exclusively to produce oil, bringing about changes in their management and morphology.

The endeavour to counter increasing land costs has, in turn, followed two strategies, often complementary in nature: i) the importation of soil/land (at a pace marked by the expansion of transport and markets) and ii) the introduction of land-saving technologies. In this respect, we should note that most of the technologies introduced since the 19th Century have managed to meet quantitative land requirements, but not qualitative or functional requirements (*functional land*). As a consequence, biodiversity has been lost and, consequently, so has sustainability.

Figure 2
Functions of agrarian land and reasons for its ‘freeing up’ for agriculture

Forest	Pasture	Agricultural crops
Land used for wood as a raw material	Land to feed revenue livestock (‘freed up’ through the importation or growing of animal feed)	Land dedicated to replenishing fertility: fallow and leguminous crops (‘freed up’ through chemical fertilisers)
Land for fuel for domestic use (‘freed up’ with the use of coal and gas for cooking and heating)		Land dedicated to crop rotation (‘freed up’ through phytosanitary treatments)
Land for fuel for industrial use (‘freed up’ with the use of coal)	Land for working livestock (‘freed up’ through replacement with mechanical technologies)	Agricultural land

The reduction of land cost was achieved through one or several of the following processes, either separately or in conjunction. Firstly, by reducing the land footprint of organic fuels on agro-ecosystems by importing charcoal from neighbouring areas (due to the high cost of transport and low energy density, this route was seldom used) or by replacing organic fuels with fossil fuels both in domestic demand and in industrial and urban demand. In this aspect, the SET was initiated with the energy transition that ‘freed up’ land for agriculture thanks to the use of coal from the start of industrialisation, especially in the 19th Century. The amount of ‘freed-up’ land varied depending on the country, owing to three factors:

a) the rate at which coal was introduced
b) the size of demand for wood for industrial users and
c) the rate at which each country followed the replacement of timber and charcoal with fossil fuels (gas and oil. In Spain, for example, this energy replacement did not occur until the arrival of butane gas in the sixties).

In second place, by reducing the land dedicated to producing feed for livestock. The importation of livestock from other territories was always limited in its scope, also due to the costs of transportation and subsequent feed. It was easier to import fodder and above all commercial feed for existing livestock and even increase numbers in an excessive way, as is the case today, returning to a diet with a high meat and dairy content (importing land and provoking food insecurity and famine in third countries (FAO, 2007). This phenomenon explains the progressive diminishment of land available for extensive livestock farming and even the appearance of livestock farms with very little land or none at all. The replacement of animal traction with mechanical means, powered by fossil fuels, constituted the most effective way of 'freeing up' land for human food and the production of raw materials. This substitution also facilitated the spread of seed varieties (cereals above all) which produced more grain and less straw.

Thirdly, by reducing the land cost of food grown for human consumption. Two converging instruments were used here: a) the importation of food or nutrients, whose rhythm and volume depended on innovations in transport. There was a long tradition in this respect: from imports of sugar, whose calorie content justified the long distances covered from the origin, to the importation of cereal, which reached a massive scale with the crisis at the end of the century. The importation of guano in the 1840s ushered in a commercial flow that is still going today and which has been fundamental in sustaining the productive intensification of European agro-ecosystems; b) the technological changes that increased efficiency in the production of agricultural biomass, boosting yields. Three innovations were vital here:

a) the technological improvement of irrigation systems which was the most effective way of boosting yields in arid and semi-arid climates;
b) the manufacture of synthetic chemical fertilisers, which allowed land dedicated to the 'manufacture' of organic fertilisers (lands used to feed livestock) to be 'freed up' and, to a certain extent, the increase in yields to be sustained;
c) the application of phytosanitary treatments and seeds that offer a high response to the use of fertilisers, water and phytosanitary treatments, which are able to improve the unit yield of harvests (the struggle against pests and disease was key to sustaining single crops and eliminating alternation of crops and fallow).

6. The stages of the metabolic change.

In accordance with all the above, a distinction should be made between three major 'waves' in the SET process of the agrarian metabolism: the first, fostered by institutional change towards capitalism, took place within the boundaries of the agrarian metabolism and signified the ‘*optimisation*’ of its possibilities raising biomass production. The second wave signified the first metamorphosis in the configuration of the agrarian metabolism through the injection of artificial nutrients, in other words, through the external *subsidy* of energy and materials from non-renewable sources. Finally, the third phase signified the total penetration of fossil fuels within the agrarian metabolism (second and definitive metamorphosis, up to the present day).

First Wave: The Organic Agrarian Metabolism reaches its limits.

In many agro-ecosystems, the SET was initiated through pressure for transformation that originated from outside of agriculture, in other words, from the urban-industrial sector which grew through stimulation by economic activity (by the industrial revolution, for example; but also through the demand for external food products) and/or through the growth of the urban population. In other agro-ecosystems, pressure for transformation was generated from within and motivated either by the growth of the population and/or impelled by institutional change which was brought about by liberal revolutions. Therefore, a distinction must be drawn between:

a) Agro-ecosystems in which the SET originates from outside the agrarian metabolism. It is precisely the incapacity of the agrarian metabolism to meet demands, especially for fuel originating in the urban-industrial sector, which initiated and impelled the transition. The scale of these demands depended on the magnitude of the industrialisation process and the economic growth experienced by the first countries to industrialise (*first comers*) in the 18th and 19th Century. The impossibility of meeting the growing demands for fuel, food, raw materials and animal traction forced change. There must even have been certain countries in which pressure came from outside, from countries that had initiated industrialisation, without the existence of significant endogenous pressure.

b) However, in countries that joined industrialisation later on (*late joiners*), pressure must have originated within the agrarian metabolism itself. The increase in the population, of consumption and trade pressures seem to be the main vectors in this change which ruptured the balances in different land uses, creating a phenomenon of increasing land shortage. The lack of land pressured institutional changes, especially in the regime of feudal property. These changes brought about four very significant changes, among others: (a) the commodification of land and other natural resources, in other words, the possibility of mobilising resources and even moving them from different parts of the territory, assigning them from that point onwards only according to abstract monetary values; (b) the rupture of the legal regime that maintained the traditional integrated system of agro-forestry and pasture uses, in other words, based on a diversified strategy and assured self-sufficiency (communal regime in its diverse meanings); (c) the implementation of agrarian policies that attempted to ensure the supply of food, which in a good many countries led to the promotion of agricultural land use (or livestock, in some cases) over others; and (d) the exacerbation of social inequalities. In England, France, Spain, Portugal and many countries in Latin America (Garavaglia, 1999) the enclosure laws or the seizure of Church lands were the kinds of institutional changes that were key agents in the processes described above.

The Second Wave: The replacement of organic nutrients with chemical ones.

Therefore, the first major metamorphosis in the AM occurred in relation to the biogeochemical cycles which were partially destructured. The vector of this process was the appearance and spread of artificial fertilisers at the end of the 19th Century. Their introduction meant 'overcoming' the most common limiting factor in production thus far, the lack of nutrients, and a break from the dependence on replenishing land fertility. In other words, *reducing the land cost of fertilisation*. A long transition process commenced in which *agrarian production shifted from depending on soil to depending on subsoil*, in other words, on fossil fuels and minerals, as is the case today.

It began in this area because the critical point in terms of the resilience of the agrarian metabolism was precisely the shortage of nutrients and/or the depletion of the soil. The successive land arrangements designed in the 19th Century to produce new essential balances became expensive and impracticable owing to their growing size. From the second half of the 18th Century onwards, the expansion of crops for industrial purposes or human consumption required the importation of soil/land in the form of organic matter or animal feed. But the continual increase of agricultural surface area and its productive intensification aggravated the nutrient deficit to such an extent that it increasingly cost more money and effort to cover this deficit by importing organic fertilisers. This created a favourable context for the spread of land-saving technologies, especially chemical fertilisers, where the process of intensification had consumed the land's own resources, which would explain the irregular use made of this technology in the early 20th Century. In places where there were still lands with which to generate new balances there was no need to use it and it was only carried out on a partial basis. A similar pattern was observed in large expanses of land, such as the *latifundios* of certain Latin American countries or in the south of Spain, Italy and Portugal, where draught livestock could be used to obtain the fertiliser required for the total or partial sowing of fallow land, thereby increasing crop intensity (see González de Molina, 2001). More intensive rotations, without fallow and with successions of crops that would have been impossible previously, were now possible, stimulated by the integration of the international markets for agrarian products at the end of the 19th Century.

Krausman, Schandl and Sieferle (2008) put back the introduction of fossil fuels in agriculture until after the Second World War, with the arrival of the third and final wave. But if we approach this issue from a broader perspective, which includes the Mediterranean world, the energy change in agriculture began in the first few decades of the 20th Century, not only because synthetic chemical fertilisers entailed high energy consumption from fossil fuels, but also because these fuels were an intricate part of agrarian labour processes. In the early decades of the 20th Century, the energy change took place in irrigation systems with underground water: waterwheels and animal drawn mechanisms were replaced with systems powered by fossil fuels (irrigation water hoisting pumps powered by electric or internal combustion engines fuelled by producer gas or oil). In Italy this was even more so, bearing in mind the spread of drainage pumps powered by fossil fuels in processes of *Bonifica*. The appearance and spread of these technologies were crucial to the agrarian modernisation of both countries (Calatayud and Martínez Carrión, 1999; Bevilacqua and Rossi-Doria, 1984; Bevilacqua, 1989-91; D'Attorre and De Bernardi, 1994).

The Third Wave: the replacement of manual labour with machines.

The third major stage in the metabolic change paved the way for the *(second) definitive metamorphosis* of organic or traditional agriculture. The energy transition was complete: fossil fuels replaced much of the manual labour and all animal traction. The agrarian metabolism became industrialised and the characteristic limitations of the organic metabolism disappeared. It was associated with the change in the energy pattern that replaced coal with oil and natural gas, which offered higher energy densities. Associated with them, two basic innovations for the industrialisation of agriculture permitted the mass subsidisation of agriculture with external energy: electricity and the internal combustion engine. This began during the 1930s in the US and reached Europe after the Second World War. It began with the mechanisation of many agricultural tasks and culminated in most rich countries with the spread of the 'technological package' of the Green Revolution at the end of the 1950s. Some of these technologies also enabled the productivity of labour to be increased, in other words, diminishing the amount of human and animal endeavour required (chemical weed-killers, pesticides, etc...).

Crop intensification had come up against new ecological conditioning factors, as had occurred in the late 19th Century. Agricultural activity had been growing relentlessly and livestock, the main source of traction, could not keep up in terms of traction demands or the change of diet, richer in animal proteins. Competition between the allocations of land to growing food or fodder will still as much of an issue as ever. The presence of animal traction impeded further expansion of agriculture and intensive livestock farming. It was necessary to develop a kind of technology that would once again save land, freeing up the labour livestock productive areas, a kind of technology that would replace animal traction with mechanical traction. Added to that was the convenience of saving costs to achieve a minimum threshold of profitability, situated at a lower level than the average profitability of other economic activities. The reduction of manual labour, replaced by machines or by chemical means that made certain tasks easier (weeding, for example) was the solution. In some countries, emigration from the countryside to the city and the development of movements of paid farm labourers pushed wages up and sped up the substitution process.

7. By way of an example: the SET in 19th Century Europe.

In Continental Europe, many countries had also been suffering from internal pressure and, to a lesser extent, external pressures on their agro-ecosystems to raise the volume of biomass production. The population increase that began in the 18th Century, the process of urbanisation, the elevation in consumption among the upper cases and the different demands being generated by the newly burgeoning process of industrialisation, converged in a legal-political structure that protected the traditional configuration of the agrarian metabolism and the distribution of land uses. This facilitated institutional change (liberal revolutions) especially in the regime of feudal ownership and the ‘liberalisation’ of agrarian markets. From that point onwards, European agro-ecosystems could meet requirements by implementing one or several of the following possibilities, depending on their provision of land and their climate and soil conditions.

i) *Pushing back the agricultural boundary* where possible.

Undoubtedly, ‘freeing up’ the energy functions of fallow and pastureland through the introduction of coal in economic activity and even in domestic consumption, facilitated the reclamation of lands and their use for crop cultivation.

There can scarcely be any doubt that it was in the United Kingdom where the SET first began in the countryside. The effects of population growth and rising energy consumption especially in the manufacturing sector put pressure on forest and woodlands, favouring the increase of croplands for the production of food. In the other direction, there was pressure coming from the growing need for fuel for homes and nascent industry. There was also increased demand for pasture and fodder to feed traction animals on which an increasingly broad and voluminous transport system depended. The extreme shortage of land caused by all these demands lay at the root of the energy change, technological innovation and, finally, the metabolic change that began with the Industrial Revolution. This was the main thesis argued by Richard Wilkinson (1973) in the seventies. According to Sieferle (2001, 38), there would have been no industrialisation without a capitalist perspective on the economy and without a ‘modern’ mentality, but also without access to new sources of energy.

The energy change brought about by the widespread use of coal had contradictory repercussions on the agrarian sector. On the one hand, it put pressure on agriculture to provide more food for a growing population, particularly in urban areas, and for an equally growing number of animals for transportation. However, on the other hand, decoupling industrial activities from the land facilitated the growth of cropland. Farmed land area grew by 58% and the area of land dedicated to cereals by 62.8% between 1700 and 1830 (Schandl and Krausmann, 2007, 87). From this perspective, the growth possibilities of agricultural production in the United Kingdom depended not only on the innovations of the agricultural revolution but also on breaking away from the rigidity of the agrarian metabolism and, therefore, on the possibility of having access to more land to meet the endosomatic consumption of its population, particularly in urban areas.

The UK exhausted the possibilities of increasing biomass production using its own resources earlier than any other European country. According to the cited authors, this circumstance became evident in the mid 19th Century. This was not the situation in most European countries, which were still far from reaching the maximum growth potential offered by their agro-ecosystems. Such was the case, for example, of Austria (Krausmann, 2001) or the Swiss canton of Berne (Pfister, 1990). As we have shown in the case of Andalusia (González de Molina et al. 2009), at the start of the 19th Century, the growth possibilities for agricultural production and even for the production of biomass within an organic metabolic arrangement were far from having reaching their limit. The work of Tello et al. (2009) in relation to Catalonia suggests the same. There were even countries in which land was abundant and its agriculture could respond. The clearest example is the United States and many other countries in the Americas such as Argentina and Brazil (Garavaglia, 1999; Padua, 2002, 2004.).

ii) *Saving land,* increasing yield per land unit.

The most well-known innovations in this respect took place precisely in the United Kingdom and gave rise to the so-called ‘Agricultural Revolution’ which, in the opinion of almost all historians, sustained the Industrial Revolution. The latest historiographical contributions, however, do not talk about sharp changes but rather the slow introduction of improvements in the 18th Century that boosted productivity (Overton, 1991; Allen, 2004). New rotations, combining cereals with leguminous crops and fodder allowed for a better association between crop and livestock farming, the increase in livestock numbers, the substitution of human labour with animal traction and an increased availability of manure, practically eliminating fallow.

According to Krausmann, Schandl and Sieferle (2008, 194), the Austrian solution was similar to that of Britain: “New crops, above all leguminous fodder, potatoes and corn were gradually included into a new crop rotation and traditional fallow was abolished. The new crop raised the availability of fodder and allowed more livestock, improved feed supply and extended stall feeding. These measures improved the availability of manure and did, in combination with the nitrogen enriching effect of leguminous crops, significantly enhance the nutrient supply on cropland. The shift to more intensive land use practices was largely compensated for by increasing employment of draught animals and more efficient iron tools. The optimisation of agricultural production allowed almost a doubling of food output in Austria between 1830 and 1910, although the agricultural labour force remained more or less constant during this period...... By and large, in Austria increases in food production kept pace with population growth during the 19th Century",

In many other parts of the world, this solution (*mixed farming*) had already been adopted (Asia) or the soil and climate conditions did not make it practicable, which was the case in the Mediterranean world. The cases studied in Catalonia and Andalusia demonstrate that. Another option, particularly suitable for dry climates, was the expansion of irrigated land and the consolidation of water supplies. In fact, this was one of the routes chosen in practically all countries on the shores of the Mediterranean, as well as in China, Mesoamerica and the Middle East (Toledo and Barrera Bassols, 2008). However, until the arrival of fossil fuels, the multiplication of the extractive power of subterranean water and the construction of large dams, the use of irrigation was limited territorially and subject to the seasonal conditions of rivers and other bodies of water. Improvements in the productivity of labour were, by their nature, limited. However, relatively important improvements were achieved with the introduction of new tools, always manual or powered by animals (which signified an added energy cost, often not practicable). The substitution of human labour for animal labour was one of the most frequently chosen paths to improve productivity. But this solution was dependent on the land available given its high land cost.

iii) *Specialising production*, promoting one land use over others.

The studies carried out in England, the canton of Berne (Pfister, 1990), certain areas of Andalusia (González de Molina et al, 2010) and Catalonia (Tello et al, 2010) show that, in general, marketable production was increased through the *promotion of agricultural crops and productive specialisation* which tended to break the balance between the different land uses that had characterised the organic metabolism.

In the practice of the three solutions outlined above, the replenishment of fertility became the crucial factor. Land imbalances made it essential to have a greater supply of organic matter. In view of the increased yield per land unit that took place throughout the 19th Century, access to a higher amount of nutrients was in theory possible although not very significant. However, there are reasons to think that in many countries the expansion of the agricultural boundary or the increase in yields was achieved at the expense of nutrient reserves accumulated in the soil over centuries, naturally or thanks to the management of farmers. Our research about southern Spain shows that the agrarian sector responded to this growing market pressure by transferring not only the internal demands of the country but also the demand for food and raw materials from the British economy, specialising above all in the production of cereals, grapevines and oil (López Estudillo, 2002; Garrabou and González de Molina, 2010). In the case of grapevines at least, and possibly olive trees as well, greater crop intensity was achieved by extracting from the soil nutrient reserve (González de Molina et al., 2010), bearing in mind the structural shortage of organic matter in Spanish agriculture (González de Molina, 2002). A similar occurrence was documented for the North American prairies by Cunfer (2005), so perhaps part of the agrarian growth experienced during the 19th Century and the first half of the 20th Century could be classified as *extractive* growth (*of 'underlying assets')* which did not have grave consequences thanks to the fast spread of chemical fertilisers.

iv) *Importing biomass* that agro-ecosystems are unable to produce.

The fourth solution, practiced abundantly albeit only up until the late 19th Century and more in inland areas of countries and between nearby countries rather than on a global scale, was to *turn to the markets to import nutrients, food for human or animal consumption*. The 'industrial revolution' was also sustained by the growing importation of food, nutrients and raw materials from other regions and countries. In around 1870, when the potential for modernisation within the solar energy-based agrarian system had been exhausted, the UK changed its economic strategy by importing growing quantities of basic foodstuffs from other parts of the world (and adjusting its surplus population via emigration). In 1900, the land area equivalent to the imported cereals achieved a similar level to the domestic availability of farm land (Krausmann, Schandl and Sieferle, 2008, 194). This flow of cereals even permitted the British agrarian sector to specialise in livestock production, which consumes a great deal of land but saves on manual labour and produced lean benefits for large English landowners. But this appropriation of more land was not always 'peaceful'; on a number of occasions, it was achieved with political-military means. 19th Century colonialism is a good example of this.

In any case, productive extensification and intensification caused the closed flows of local production to collapse, expanding their scope and entering supralocal markets created in part by the expansive dynamic of specialisation. In these broader markets, not only are products exchanged but also production factors, especially fertilisers, thereby initiating a process of commodification and the subsequent unrelenting specialisation of production. Although the difficulties of land transport made it unadvisable to import organic fertiliser (large volume and very high amounts required), some countries in Latin America such as Peru firstly and later on Chile became suppliers of some of the nutrients (guano) required by European agriculture to continue growing. However, one must put the importance of transatlantic flows of nutrients in the growth of agrarian production in Europe into perspective. According to Smil (2001), the global production of nitrogen from guano and mineral nitrates reached 240,000 t in the year 1900. More important were the importations of land/soil via food and animal feed.

Indeed, through commercial relations, major importations of land/soil occurred which, through different means, compensated for the imbalances in the agrarian metabolism of the origin societies. *The organic metabolism of these societies was impelled to jump from one equlibrium state to another, situated on a greater geographical scale, where new territorial balances had to be constituted*. Whereas the first and longest-lasting balances were established in local spheres, the increase in the size of the metabolism obliged territorial integration on different scales. For example, in inland continental areas, where the means of transport was still land-based, territorial balances were established within districts or provinces, with flows still limited to a national scale. However, in areas with good sea transport links and their hinterland, balances could be established with far-off lands through commercial or colonial flows. Many port cities around the world specialised due to the fact that they could import energy and the materials they would no longer be producing with their new dedication.

The possibilities of maintaining the sustained growth of agrarian production through the progression of agricultural cultivation or the increase in the land’s productivity were exhausted. In countries such as the UK, this occurred early on, in others later, but most European agro-ecosystems had reached their productive limits by the end of the 19th

Century. The cases of Catalonia and Andalusia certainly suggest that. The case of Andalusia, with the progression of woody crops, also compels us to analyse whether some of the processes of productive specialisation and agrarian growth that took place in certain regions of Spain were achieved at the expense of the soil nutrient reserves, making the system even more unsustainable.

The exhaustion of the growth possibilities of agrarian production in the second half of the 19th Century in many parts of Europe points to the threat of a ‘Malthusian crisis’. The technological change, in other words the arrival of synthetic chemical fertilisers, was still a way off and spreading around the countryside. This hypothesis points to the need to revise from this perspective the emigrations that took place in Europe in the second part of the century or the expansion of the international food market. It was precisely the need to import growing amounts of food from overseas that fostered improvements in transport and, paradoxically, provoked the agrarian crisis at the end of the century.

In any case, the studies available about the replenishment of fertility (Krausmann, 2006; Tello, et al., 2209; Cunfer and Krausmann, 2009; González de Molina et al, 2009) confirm that this became a key factor in the sustainability of the Organic Agrarian Metabolism and which effectively played a key role in the process of transition towards an industrial agrarian metabolism. The emergence from the end-of-century crisis, based on productive specialisation and the increase of yields per land unit, was only practicable when the structural shortage of fertilisers could be overcome, as argued previously elsewhere (González de Molina and Pouliquen, 1994; González de Molina and Guzmán Casado, 2006), through the manufacture of synthetic chemical fertilisers with fossil fuels.

From the aforementioned research, it is possible to draw an important conclusion: the end-of-century crisis might be explained not only by the entry of cheaper grain in Europe, but also by the friction of two types of farming systems with different mechanisms for replacement of soil fertility. The land costs of European agriculture, and particularly in the Mediterranean, were higher than in America and Australia. In the absence of chemicals fertilisers, the replacement of soil fertility needed land devoted to producing manure or plant legumes. Since European agriculture had continuously cultivated soil for hundreds of years, agrarian growth could not be based on the soil nutrient reservoir for much longer. Moreover, the productive intensification experienced by European agriculture during the 18th and 19th centuries decreased the capability to replenish all nutrients harvested. Hence, the productive specialisation and the increase in yields achieved during the first agricultural revolution were progressively exhausted. This was not the case in other countries such as the United States or Australia, where the soil nutrient reservoirs of recently cultivated arable land were high. The land cost of replacing soil fertility in these regions was much lower. The end-of-century crisis which was reflected in lower prices for overseas agrarian products occurred when the revolution in maritime transport caused two types of agricultural systems with rather different land costs to come face to face. So, relative scarcity of nutrients, exacerbated by the failure of territorial equilibrium resulting from production growth during the 19th Century in Europe, is one of the major reasons which caused the crisis at the end of the century and initiated the second wave of the agrarian socio-ecological transition.

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