Sociometabolic transitions in subsistence communities: Boserup revisited in four comparative case studies

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Abstract

In the context of sustainable development, we investigate four subsistence communities, one each from India, Bolivia, Laos and Thailand, to understand the systemic interrelations between the food production systems and related environmental pressures. In doing so, we revisit Ester Boserup's theory of increasing land productivity at the expense of declining labour productivity as a consequence of agricultural intensification. Our data confirm Boserup's assumptions within the reach of traditional agriculture, but find them not to apply to hunting & gathering communities and to agricultural systems now increasingly dependent on fossil fuels and industrial fertilizers. Instead we propose a theory of "sociometabolic transitions" as being more appropriate to understanding transitions in land and labour productivity across a wider range of modes of subsistence.

Keywords: *sociometabolic regimes, sociometabolic transitions, farming systems, time use, labour and area productivity, rural development*

Introduction

Since the 1960s, the study of rural subsistence communities has received considerable attention within anthropology and human ecology. Interest in the allocation of land and household labour in farming systems and the diversification of rural livelihoods in response to ubiquitous development efforts have been at the core of such enquiries (Boserup 1965, Clark & Haswell 1967, Chayanov 1966, Geertz 1963, Lee & DeVore 1968, Sahlins 1972, Wilkinson 1973, Ellis 1998, Hunt 2000, Amanor & Pabi 2007). In the context of discussions on global environmental change, these concerns have evoked renewed interest among scholars concerned with social and ecological sustainability (e.g. Gowdy 1998, Costanza et al. 2007, Tainter 2006, Sieferle 1997b, Fischer-Kowalski & Haberl 2007). As almost half of the world's population still lives in rural areas on subsistence agriculture, gathering, hunting and fishing (UNDP 2007), the direction these communities will take is extremely crucial in terms of future trajectories of global resource and land use.

While the industrialized world seeks for pathways away from and beyond fossil fuels, the dominant development model for those rural communities is still the eventual industrialization of their agriculture — fuelled with fossil energy — and the absorption of a large fraction of their population into the industrial labour market of growing cities. This appears to be the only chance for an escape from poverty, ill-health, and illiteracy. In contrast, sustainable development requires a broader search for pathways where short-and-long term benefits for the people come at the lowest possible environmental cost and avoids increasing the burden and stress on the people in terms of working time (Haberl et al. 2004; 2011). To this end, there is an urgent need to look beyond simple evolutionary sequences of responses to population and market pressures and the adoption of modern technologies, as well as beyond single variables of land and labour productivity and return upon investment. Instead, an understanding of the complex relationships within socio-ecological systems requires looking more systematically at the broad range of dynamics and pressures the social system exerts upon its environment, and how these pressures change with development.

In this paper we compare four rural subsistence communities in different stages of agricultural intensification to understand the systemic interrelations between the food production system and environmental pressures as a consequence. In doing so, we revisit Ester Boserup's (1965) theory of agricultural change, in particular her hypothesis on rising area productivity at the expense of declining labour productivity in consequence of intensification in traditional farming systems[2]. The relevance of Boserup's contribution in understanding agricultural change in traditional farming systems is well acknowledged. However, our findings reveal caveats in this theory when applying it to agricultural systems now increasingly dependent on fossil fuels and industrial fertilizers. Instead we propose a theory of sociometabolic transitions as being more appropriate to understanding agricultural development under contemporary conditions in the context of discussions around ecological sustainability and global land use change.

We begin by introducing our key theoretical assumptions and concepts, followed by a brief description of cases and methods used in data collection. We then present the main findings, concluding with an evaluation of our hypothesis and our theoretical framework.

Theoretical assumptions and concepts

Our point of departure is the theory of *sociometabolic regimes* as developed by Sieferle (1997a, 2001) and further elaborated by him and other authors since (Fischer-Kowalski et al. 1997).The theory claims that, in world history, certain modes of human production and subsistence can be broadly distinguished that share, at whatever point in time and irrespective of biogeographical conditions, certain fundamental systemic characteristics derived from the way humans utilize and thereby transform nature. Key to distinguishing *sociometabolic regimes*, according to Sieferle (1997a) is the source of energy used, and the main technologies of energy conversion. Traditional subsistence systems such as hunters & gatherers and the agrarian depend (almost) completely on the solar energy flux and its fixation through plant photosynthesis. The crucial difference between the energy regime of hunting & gathering and agriculture is the conversion technology. While hunters & gatherers are "passive" users of solar energy, that is they utilize plant and animal biomass wherever they find it, the agrarian regime relies mainly on an "active" utilization by *colonizing* (see below) terrestrial ecosystems. In other words, peasants try to channel solar energy onto a few plant species they wish to use by changing the land cover and seeking to monopolize selected quality land for their food and feed purposes, albeit at the cost of more human labour that further increases with agricultural intensification. The industrial sociometabolic regime, on the other hand, transcends the limitations inherent in relying on the current flux of solar energy by utilizing fossil fuels, the stock of historical solar fluxes accumulated over millions of years.

The transitions between sociometabolic regimes are unlike what is often understood as an incremental change in material and energy use in societal development (White 1949). Instead, the shift between energy regimes is associated with a major transformation of society. The grand shifts in the past (the Neolithic and the Industrial Revolution) have allowed for an enormous increase in energy and material use, boosting metabolic rates (Haberl et al. 2011). However, sociometabolic regimes, according to this theory, are not something static. Rather, they are constituted by a set of opportunities and constraints within which certain dynamics take place. But if the dynamics transcend or are pushed out of the boundary conditions of the regime by exogenous forces, turbulence will ensue with an unpredictable outcome anywhere between collapse of the social system (Tainter 1988, Leemans & Costanza 2005) and a transition into another sociometabolic regime (Fischer-Kowalski & Haberl 2007). Below we introduce two interrelated concepts that allow us to describe the structure and dynamics within and between sociometabolic regimes — social metabolism and colonization of natural systems — and how the varying forms of higher level interventions affect these.

Social metabolism

Social metabolism draws on an organismic analogy by claiming that any social system not only reproduces itself culturally, by communication, but also biophysically (namely its population, built infrastructure, man-made artefacts and livestock) through a continuous energetic and material exchange with the natural environment (and eventually with other social systems). Social metabolism can be quantified in terms of energetic and material flows per time period, usually a year. The size of the flows required depends, on the one hand, on the size of the biophysical structures (or stocks) of the social system (i.e. the size of the human and livestock population, and all human-made infrastructures), and on the sociometabolic regime, on the other hand. Different sociometabolic regimes have substantially different *metabolic profiles* (i.e. quantity and quality of materials and energy used). Metabolic profiles can be expressed as total quantities for a complete social system (a society, a community, or, for example, a household), and they can, for reasons of comparability, be referred to the number of the human populations the social system sustains, and are calculated as *metabolic rates* (in terms of energy or materials required per person and year). The higher the metabolic rate, the more resources per inhabitant have to be extracted or imported and the more outflows of wastes and emissions are produced, therefore the higher is — other things being equal — the impact upon the environment. Once adequate boundaries of the social system are defined (and this has received a great deal of methodological attention by a number of researchers; see for example Fischer-Kowalski & Hüttler 1998; Matthews, et al. 2000; Schandl, et al. 2002), biophysical structures (stocks), flows, metabolic profiles and metabolic rates can and have been measured or estimated in a comparable way for a number of social systems (communities, societies) on various scales across history (for an overview see Fischer-Kowalski & Haberl 2007).

Colonization of natural systems

The second concept employed for characterizing the respective society-nature interaction is *colonization* (Fischer-Kowalski & Haberl 1998). Social systems not only exchange energy and materials with their natural environment, they also deliberately intervene into natural systems with the intention of transforming them in ways they consider more useful for themselves. A classic colonizing intervention is changing the land cover in favour of agriculture, but this term can usefully be applied to processes as varied as animal breeding, genetic modification or dam building. The important commonality is that natural systems thus transformed by human intervention are usually brought into a state far from the relatively natural state, and need a continuous input of human labour (and typically also energy and materials) to be kept in that state. Thus a social system's colonizing activities are related not only to the effort that must be invested both in terms of working time (quantity), but also to the use of certain technologies (quality). The more a society modifies its environment, the more metabolic returns it may expect, but also the more efforts it has to expend to keep it in the desired state — and this may create the need to invest even more working time. Only by using the "subterranean forest" of fossil fuels (Sieferle 2001), in connection with industrial tools such as machines and synthetic fertilizers, can the relation between intensification and increasing working time be broken.

The relationship between land use and labour has received considerable attention since the publication of Ester Boserup's *The Conditions of Agricultural Growth* (1965) where she argues that in traditional subsistence systems, in response to population pressure, technological development takes place leading to an intensified use of land sustaining more people, but at the expense of a higher input of human labour. While an advantage in terms of land productivity (where land is a limiting variable), it is not so in terms of labour input per unit of harvest. In this sense, intensive agriculture needs to maintain a larger pool of labour to maintain and reproduce the colonized system. With less of a positive connotation, Geertz (1963, p.80) had termed this same process of increasing land productivity through increasing labour input for feeding more people just at the same level as before "agricultural involution" and considered it an ultimately self defeating process.

Notwithstanding, it is imperative that there is a positive net energetic return upon investment (EROI) between labour invested and harvest gained on a system level (measured in energy units). If a society invests more energy than what is gained in terms of crop harvest, this system cannot be sustained for long, unless it compensates this loss from another energy source that produces a surplus. Thus, traditional agrarian systems, with biomass as the main source of energy will strive to retain a positive EROI at an aggregate system level even as labour productivity declines but as long as land productivity increases. With the introduction of fossil fuels and related technology into agriculture, the decoupling of land, labour and energy occurs.

In other words, land is no longer a limiting variable when it comes to harnessing energy. Market prices and subsidies for fossil fuels play an important role in maintaining low, if not negative overall EROI.[3] Such a system is unsustainable from the point of view of both future energy availability as well as the environmental impact these technologies have.

Interactions between system scales

In the age of fossil fuels, industrial production and improvements in transport and communication, we cannot expect our case studies dating at the beginning of the 21st century to comply with the typical pre-industrial mode of production in full, however isolated they may be. Therefore, interventions from higher scale systems already affected by the industrial transformation must be considered. They most likely have an impact on the metabolic profile and on the social dynamics of the local subsistence system under consideration. Four types of interventions were found to be most common which we categorize as follows: (a) *provision of services* such as health and education, (b) *regulatory mechanisms* from the state such as introduction of legal instruments and market conditions, (c) *supply of (often subsidized) fossil-fuel-based technologies* either through agricultural extension programmes (machines, mineral fertilizers) and/or by introducing electricity and communication network and transport infrastructure in the region, thus enhancing opportunities for marketing produce, buying commodities from outside, and labour migration thereby modifying the local production and consumption patterns, and (d) *supply of specific aid and subsidies* either as part of general welfare policies, or as part of famine or disaster relief. Such interventions buffer communities from responding to extreme events using their own traditional and self-organization capacities as may have been in the past.

Description of the four cases and context

The first case is Trinket Island in the Nicobar archipelago (India) with 399 inhabitants in 2001. The community exhibits an economic portfolio that combines hunting, gathering, fishing, pig and chicken rearing, growing coconuts and bartering *copra* (dried coconut meat used as raw material in the extraction of oil) in lieu of rice, sugar, cloth, kerosene, and other necessities on markets located on neighbouring islands. A few families maintain food gardens where they grow an assortment of crops such as bananas, pineapples, yam, sugarcane, oranges, lemons, papaya and jackfruit. Simple metal tools such as sickles, axes and spades are used for clearing, planting, or harvesting. Since the 1980s, the Indian government has gradually introduced a variety of welfare programmes for the Nicobarese such as education, health services, transport infrastructure and a variety of subsidies including the sale of cheap diesel and kerosene (Singh & Schandl 2003, Singh et al. 2001; Singh & Grünbühel 2003).[4]

The second case is Campo Bello (Bolivia) with a population of 231 inhabitants in 2004. Campo Bello is characterized by swidden agriculture, fishing, hunting, gathering and raising poultry. Rice is the most important crop, but the villagers also grow plantains, maize, manioc and others of lesser importance, such as peanuts, sugar cane, citrus and varieties of sweet potatoes. The technology employed in agriculture is simple, using only machetes, hoes and rice seeders for the sowing of rice. A certain amount of rice and plantains are sold in the market for cash or barter. Wage labour is also sold by younger men. The village has witnessed a number of development projects introduced by the local administration and non-governmental agencies. Development efforts include the construction of a school building made of concrete in 1993, the installation of electricity for the school building, a solar panel for the operation of a communal telephone, and the installation of several individual latrines and concrete wells. In 2006 and still ongoing, a new project involved various families in the cultivation of beans and the raising of poultry.

The third case studied is the multi-ethnic community of Nalang (Laos) with a population of 702 people in 2001. Nalang is again a subsistence economy dominated by rainfed rice farming, primarily through permanent paddy farming and also shifting cultivation. In very productive years, a harvest surplus may either be sold to other villages or to outside traders. In the late 1990s, the production of cucumber was introduced as an important cash crop during the dry season. Gathering, fishing & hunting activities are also common. To catch fish, people apply a variety of techniques ranging from line fishing to casting nets. Hunting is carried out either by using traditional hunting devices like traps or bows or more elaborate home-made guns. Some buffaloes are still reared for use in agricultural work and general transport. The arrival of the motor-plough in the mid 1990s, however, has diminished the need for buffaloes, and for meat production, buffaloes have largely been replaced by cattle, since their maturing times are more rapid. The construction of a road in 1980 allowed some to engage in wage labor.

The village of Sang Saeng (Thailand) with 171 inhabitants was investigated in 1998. Sang Saeng's economy revolves around permanent rice farming, raising livestock, foraging and labour migration. While the glutinous rice is grown only for subsistence, non-glutinous varieties are specially produced for the market. Villagers own vegetable gardens and keep chicken and ducks for their own consumption. Buffaloes are raised as working animals, but cattle are destined for the local market. Hunting and gathering activities also feature prominently: foraging helps to diversify the diet, especially during the dry season, when gardening is limited or made virtually impossible. During the dry season, temporary migration for wage labour to urban centres or to coffee and rubber plantations in southern Thailand is now rather common, with the labourers returning in time for the peak agricultural period for preparation of rice nurseries, ploughing, transplanting, and harvesting. Threshing machines, electrical water pumps, non-potable water supply, electricity, and a semi-permanent road are a consequence of government interventions.

Methods

The four cases were studied by members of our team between 1998 and 2006. The field research in each of the communities extended over several months. To all of the communities, there were also follow-up visits to cross-check on data.[5] Here we focus only on describing the methodology for outlining the social metabolic profiles of these communities as well as aspects of their land-use and labour input.

To define the characteristic metabolic profile for each of the social systems, we adapted the standard national Material and Energy Flow Accounting (MEFA) toolbox as prescribed by the Statistical Office of the European Union (Eurostat 2001; Eurostat 2007) to the local context. Local material and energy flow accounts were created following a number of steps: (a) *defining the systems boundary* of the socio-ecological system under investigation according to systemic and pragmatic considerations, in particular concerning population and the territory the social system is entitled to exploit (legally or by tradition), (b) *identifying the biophysical stocks* that the community maintains and reproduces year after year, such as human population, domesticated livestock and man-made artefacts (buildings, wells, pathways, boats, and machines), (c) *quantifying flows of materials and energy* that the society organizes to maintain and reproduce its biophysical stocks. These flows may originate from the domestic environment (*domestic* extraction) or they may be *imported* from other social units. Equally, on the output side we differentiate between *wastes and emissions* that are deposited onto the domestic environment and *exports* to other social units (for details on local MEFA methods, see Singh et al. 2010).

Local-level data is not as readily available as for national accounts. They have to be generated using a combination of innovative, often labour and time-consuming techniques of on-site quantification. The stock account of the social system is based on an inventory of the local population, livestock and the most important human-made structures. Livestock and artefacts are expressed in metric tons: this was done by actual weighing or by drawing on factors from externally available sources. Flow data were generated by sample weighing and estimations. All biomass flows were calculated both in terms of weight of dry matter and fresh weight when harvested[6] or traded. For energy flows and energy conversion processes, the same system boundaries as in material flow accounting were applied (Haberl 2001, 2002). Material flow data for biomass and fossil fuels were converted to energy units by using calorific values. The indicators generated are standard indicators developed in the framework of material and energy flow analysis on the level of national economies (Eurostat 2007; Haberl et al. 2004), and they express the amounts actually used by a social system during the course of a year. Derived indicators express these flows per capita population as *metabolic rates*.

Land use was studied according to the same system boundaries. First, we accounted for the 'total area' controlled and used by the social system, corresponding to the territory as defined above (Singh et al. 2010). We mapped the total land cover of this territory according to use and according to ecosystem types, such as primary and secondary forests, grasslands, mangroves, horticultural gardens and agricultural fields. Data for land-cover and ecosystem types were either taken from official statistics (especially in case of forests, grasslands, mangroves and beaches) or measured by the researcher (as in the case of settlements, agricultural fields and coconut plantations). Various indicators are generated by referring material, energy and labour time flows to respective areas.

While elaborate time allocation studies were undertaken for all four cases for a sustainability analysis (Fischer-Kowalski, et al. 2010), in this paper we only focus on labour time in staple food production. Such activities were repeatedly observed (sample size 3-5 observations for each activity) and records were made how long they lasted and who (in terms of gender and age) participated in them. These activities were then weighted according to their annual frequency and thus the average daily hours could be calculated. In order to arrive at system level data, the frequency of these processes across the year was estimated and used for weighing. Labour patterns were taken into account to accommodate for seasonal fluctuations of time use allocation, and data eventually needed to be adjusted.

Findings

We organize the presentation of our findings in the following manner: first, we present the basic demographic and sociometabolic data that will allow us to classify our cases by — to use Boserup's term — degree of agricultural intensification. In a next step, we go more deeply into the issues of land and labour productivity and seek to test Boserup's formulation of the dynamics of agricultural intensification.

Table 1 gives an overview of basic demographic and sociometabolic features of the four communities. If we consider population density as a certain indication of population pressure on land, we find Trinket to have by far the lowest density (11 persons / km^2), along with a low rate of population growth. Campo Bello and Nalang have an intermediate population density (around 40 persons / km^2), and fairly high population growth rates (3-4% annually). Sang Saeng has a high population density (93 persons / km^2), but its population growth rate is similar to Trinket.[7]

Concerning the sociometabolic parameters (*table 1*), all

Table 1. Demographic features, basic sociometabolic characteristics and the food system

	Trinket hunting + gathering	**Campo Bello** shifting cultivation (short fallow periods)	**Nalang** intensive rice cultivation	**Sang Saeng** intensive rice cultivation
demographic features				
Population (cap)	399	231	702	171
Size of territory (ha)	3626	615	1630	184
Pop density (cap/km^2)	11.0	37.6	43.1	92.9
Pop growth (%/yr)	1.5	3.8	3.0	1.4
Share of population below age 15 (%)	39	61	45	n.a.
basic sociometabolic parameters				
Material metabolic rate (t/cap/yr)	3.7	1.6	2.6	3.6
Share of industrial products in the materials used (%)	0.3	1.3	0.4	13.9
Energy metabolic rate (GJ/cap/yr)	29.5	20.6	26.3	40.5
Share of fossil fuel in energy used (%)	6.4	1.0	1.5	8.3
food production and consumption				
food consumption (GJ/yr)	1752	940	3320	666
imported food (% of consumption)	29	20	1	49
food production (GJ/yr)	2820	1840	3752	2213
exported food (% of production)[1]	48	38	18	85
staple food production (GJ/yr)	**2979**	**1590**	**3101**	**2098**
area for sfp, incl. fallow (ha)	29	200	139	146
labour hours for sfp (1000h/yr)	25	114	213	83
fossil energy inputs in sfp (GJ/yr)	0	0	171	446

Notes: Material metabolic rate = annual domestic extraction of biomass + minerals for construction plus all imported materials, minus exported materials, in tons, divided by population numbers. Energy metabolic rate is the analogue, expressed in Gigajoule per capita. Staple food is rice, cereals and tubers; in the case of Trinket it is copra.

four communities are characterized by very low metabolic rates, which are typical for traditional subsistence communities. Their energy metabolic rates of 20-40 GJ are by an order of magnitude smaller than the metabolic rates of roughly 200 GJ in the European Union or even 400 GJ per contemporary US citizen (Haberl et al. 2006)[8]. Similarly, the material metabolic rates range between 1.6 and 3.7 tons per capita —this compares to 13 tons per contemporary inhabitant of the European Union (Weisz, et al. 2006)[9]. It is apparent that the communities are largely self-sustaining: of all materials that are being consumed annually, only a very small share are (imported) industrial products (between less than 1 up to 14% in terms of weight), and the energy metabolism is largely based on biomass; fossil fuels amount to less than 10%. Thus, we are dealing with communities far away from the industrial sociometabolic level.

Beyond those shared characteristics, some numbers stand out. Trinket's energy metabolic rate is higher than in both Campo Bello and Nalang, and its share of fossil fuels in total energy consumption at 6.4% also exceeds the respective share in Campo Bello and Nalang (*table 1*). Fossil fuels are only used in transportation: there is government supply of diesel for running motored boats that the Nicobarese use for transporting copra to trade for rice and other goods. And as they get this diesel delivered as imports, it by definition counts as part of their domestic consumption. In the case of Campo Bello, in contrast, it is the traders who visit the village for trading rice with pasta or alcohol, so their transport fuel does not count as part of Campo Bello's metabolism. Another noteworthy difference concerns Sang Saeng: here the per capita energy use is twice as high as in Campo Bello, the fossil fuel share approaches 10%, and industrial commodities are used much more frequently than anywhere else.

Information on the food system allows an insight in the relative position of each of the communities. In all four communities, there is about the same amount of food available for daily consumption (i.e. between 11,000 and 13,000 kJ, or 2,700-3,200 kcal per day and inhabitant). The origin of this food is different, though. All communities gain a certain fraction of their food from hunting/fishing/gathering; while this amounts to 16% or less in Campo Bello, Nalang and Sang Saeng, it is 69% of all food intake on Trinket (*Figure 1*). Thus in terms of the food consumption system, Trinket stands out as a community predominantly based on a hunting and gathering mode of subsistence.

Another important feature of these communities is their degree of self-sufficiency versus market integration. Clearly, Nalang is the most self-sufficient community: it only imports

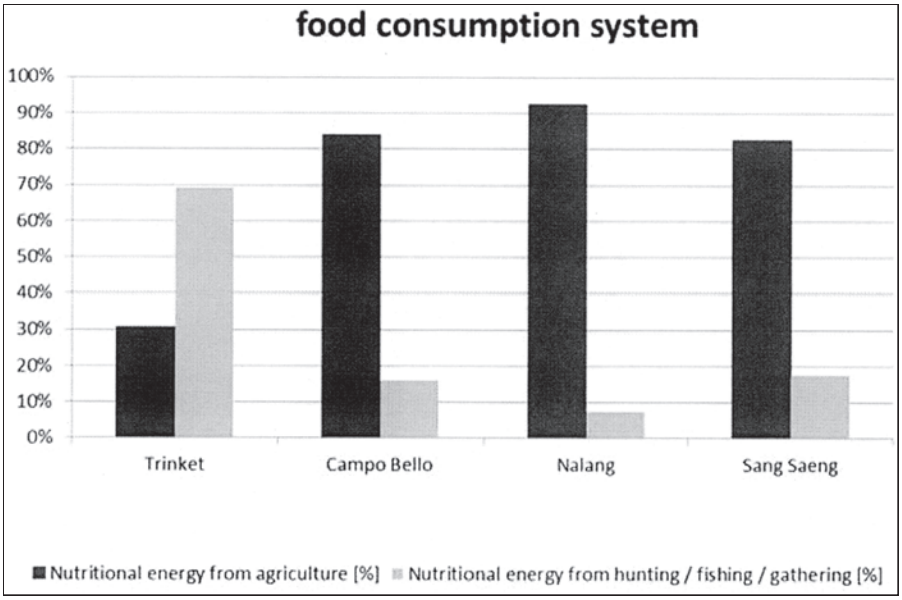

Figure 1. Annual food consumption by its origin from agriculture or foraging

Notes: this includes all the food consumed by the members of the community, irrespective of it having been extracted domestically or imported from outside

1% of the food it consumes, and it exports only 18% of its production (*Table 1*). At the same time, Sang Saeng stands out in market integration, with imports amounting to 49% of its food consumption, and exports as high as 85% of food production. All four communities are net exporters of food (if consumption is set in relation to production, see *Table 1*), and thus they are suppliers of food to the society at large, but to varying degrees.

For the remaining analysis, we shall focus on staple food production[10] and standard agroecological indicators to secure comparability among our cases and with other similar data (see Clark & Haswell 1967). While the basic information can be found in *Table 1*, we visualize our main findings in Figures 2-4. We will from now on pursue the key Boserupian (1965, 1981) hypothesis of an endogenous process of agricultural intensification (in the course of mounting population pressure and development) leading to increased yields per unit area, at the expense of increased labour input and possibly declining labour productivity. In our tables, we have tentatively ranked the communities studied along a “Boserupian axis” from Trinket to Sang Saeng; across the fairly similar cases of Campo Bello and Nalang. The data presented so far have to a certain degree confirmed such a ranking. But what we can see in *Figure 2*, displaying land and labour productivity across the four cases definitely warrants a different interpretation.

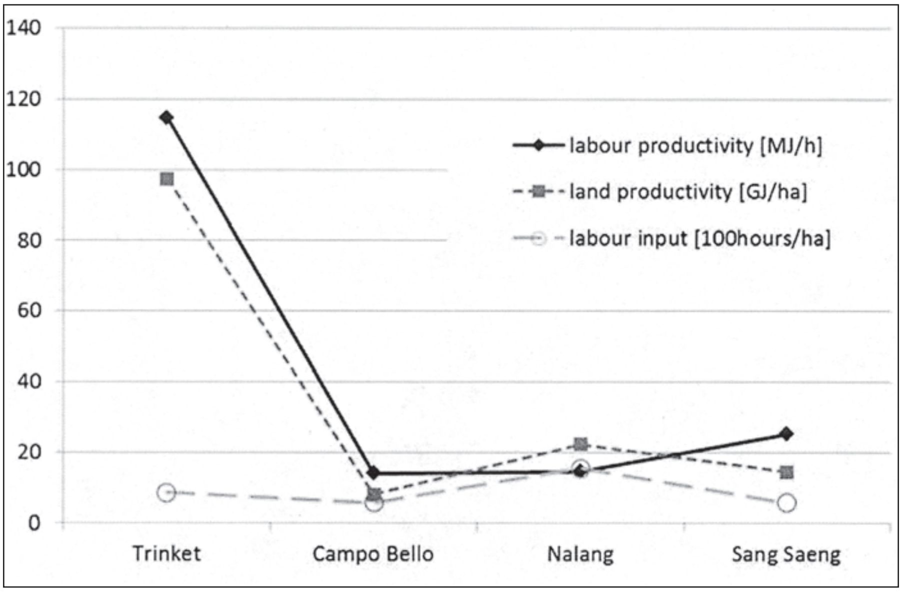

Figure 2. Labour productivity and land productivity in staple food production

Notes: Labour productivity is measured as energy content of the annual harvest of the staple food per hour worked for staple food production. Land productivity is measured as annual harvest of the staple food per hectare agricultural land (including fallow land). Labour hours are annual hours worked for staple food production per unit area of staple food production.

The results presented in *Figure 2* demonstrate for Trinket substantially more favourable conditions than for any other of the four communities. Both land productivity (in the sense of how much land is required to produce a certain amount of nutritional energy) and labour productivity (signifying how much work is required to realize this energy harvest) are far higher than in any of the other communities.[11]

Looking at this from another angle, it appears that no incremental evolutionary pathway of “agricultural intensification” would lead from a — however untypical — sociometabolic system of hunting and

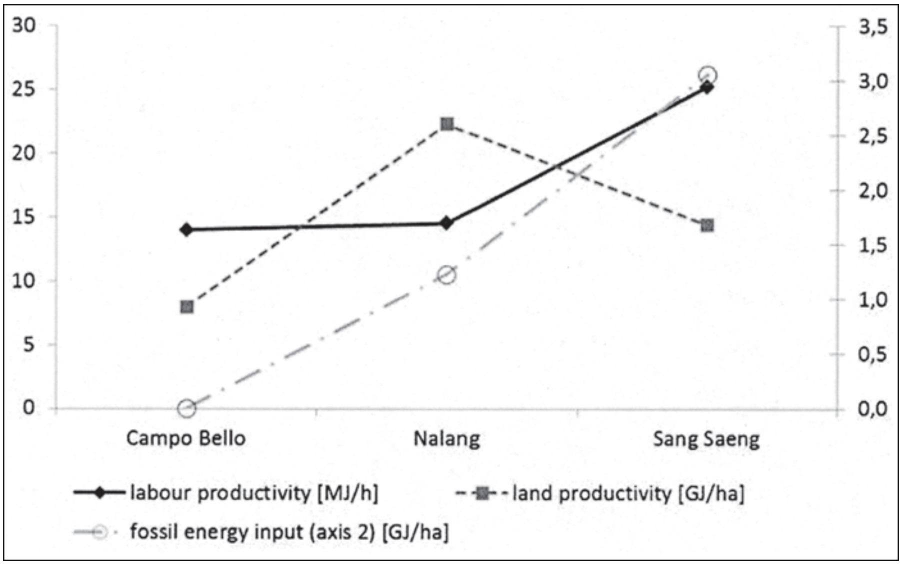

Figure 3. Labour productivity, land productivity and fossil energy input in staple food production

Notes: Labour productivity is defined as the annual staple food harvest (in energy units) per labour hour invested for its production. Land productivity is defined as the annual staple food harvest (in energy units) per unit land used for staple food production (incl. fallow land). Fossil energy input is confined to direct input into staple food production (i.e. diesel for agricultural machines).

gathering like Trinket to anything like the other communities. It would appear completely absurd to invest additional labour time into additional land for so relatively little return. Thus, a sociometabolic system like in Trinket will keep on or else collapse - but cannot gradually be transformed into an agrarian system like we see in the other cases.[12] In effect, rather our hypothesis of distinct sociometabolic regimes is confirmed: communities like Trinket adhere to a sociometabolic regime of hunter & gatherers, however untypical, and there is no continuous, non-disruptive pathway leading from this regime to an agrarian regime. It takes a major transformation, a "transition" (Fischer-Kowalski & Rotmans 2009) for a community to transcend this mode of subsistence.

We can see that Campo Bello is a "traditional" (Boserup 1981) production system in the sense of not using fossil fuel based inputs or even animal traction. In Nalang there is already some fossil fuel input (1.2 GJ/ha), while Sang Saeng uses 3.1 GJ of fossil fuel per hectare. In industrial cereal production systems, the corresponding use of fossil fuels amounts to a value of between 3 and 7 GJ/ha (e.g. Bonny 1993; Golley et al. 1990; Swanton et al. 1996; Tsatsarelis 1993)[13] Thus Sang Saeng is already an industrialized agricultural production system. And of course, a tractor is an enormously labour saving device in agriculture! Taking into account fossil fuel use, the relation between Campo Bello, Nalang and Sang Saeng would probably comply to the Boserupian hypothesis: without fossil fuels, Nalang and Sang Saeng would probably have a much lower labour productivity than apparent in *Figure 3*. Beyond that, there is a lower productivity of land in Sang Saeng than in all other cases. This may have geographic reasons (Sang Saeng lies in a relatively arid region), but it may also be causally related to long term over-exploitation of the land.

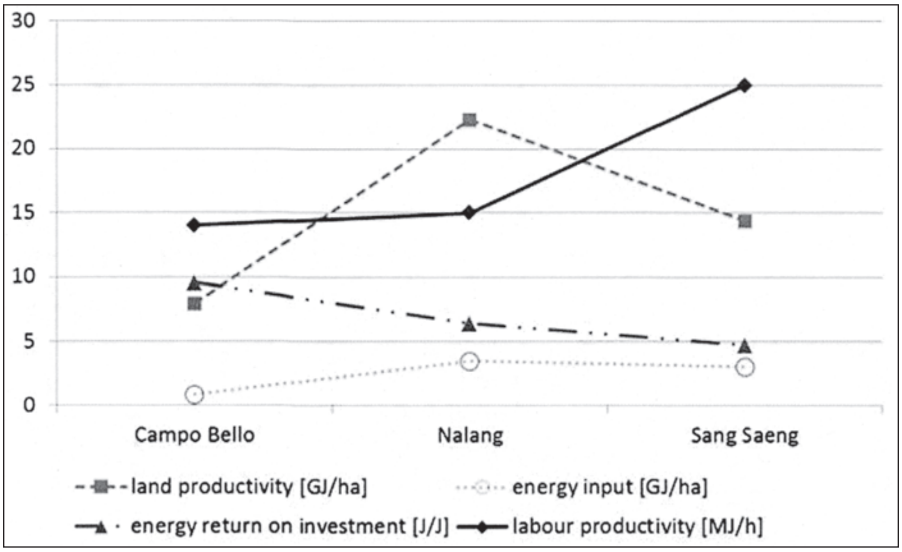

Figure 4. Energy input, energy return on investment (EROI), and land and labour productivity in staple food production

Notes: Energy input is the sum total of labour input (in energy units) plus fossil fuel input. EROI is defined as annual staple food harvest (in energy units) divided by the energy input into its production (labour hours in energy units, plus fossil fuels). Based on the according numbers given by Smil (1991, pp.86-89), we derive the energy input per labour hour by multiplying the basic metabolic rate (BMR) of 288 kJ/hour for males and 234 kJ/hour for females by a coefficient for moderate activities of 5.45 for reference males and 4.85 for reference females. The average value for all agricultural work of 1.46 MJ/hour is based on the assumption that three fourths of all agricultural labour is done by men.
1 In case of Trinket, referring to staple food only!

How can we capture this combined effect of (latently) declining labour productivity masked or compensated for by the use of fossil fuel driven machinery? In *Figure 4* we make an effort in this direction: we add two indicators to the already presented indicators of land and labour productivity. One indicator is total energy input into the food production system: it is the sum of human labour (calculated in energy units) and fossil fuel input, both per unit area. This indicator, as was to be expected, shows a clear rise in the direction of "agricultural intensification": while in Campo Bello energy investment per hectare amounts to 0.8 GJ/ha/year, it is about four times as much in Nalang (3.4 GJ/ha/year) and Sang Saeng (3.0 GJ/ha/year).

If on top of this we wish to capture the effect of lower area productivity (as apparent for Sang Saeng), we need to turn the attention to the "energy return on investment" (EROI). This classic parameter relates energy output (in the form of harvest) to energy input (labour and fossil fuels). What we then see is a clear decline along a pathway of intensification and industrialisation. While in Campo Bello, the energy harvested is almost ten times as much as the energy input, it is only 6.5 times as much in Nalang and not even five times as much in Sang Saeng.

Conclusion

Does the theory of sociometabolic regimes allow ordering our four case studies? Does it make sense to distinguish between "endogenous" and "exogenous" dynamics, and can we explain regularities and irregularities reasonably that way? Our findings tend to comply much better with the theory of sociometabolic transitions than with the classical Boserupian theory. There seem to be substantial qualitative differences between the hunting & gathering regime that only thrives if there is a high land productivity that requires little work (here exemplified by Trinket in a number of ways), the regime of non-fossil-fuel-based (subsistence) agriculture as exemplified by Campo Bello and Nalang, and a fossil-fuel-based industrial regime which Sang Saeng is stepping into. With increasing inputs of fossil fuels into agriculture, the Boserupian link between decreasing labour productivity and increasing population density is overridden by the industrial link between increasing use of fossil fuels and industrial technology increasing labour productivity.

Our results point in the direction of our theory of regime transitions, and the crucial role of working time. While of course there are numerous small steps that lead from the sociometabolic regime of hunting & gathering to agriculture (and in most agrarian communities there are still elements of hunting & gathering preserved), in terms of labour this seems to imply a major transition, requiring maybe shocks or strong pressure beyond gradualism. Similarly, as far as our few cases warrant even a tentative conclusion, the "Boserupian" endogenous dynamics looks plausible among agrarian communities, but as soon as exogenous variables substantially come into play, such as fossil fuels and other development interventions in the form of infrastructure and markets, a dynamics towards some kind of "transition" leading out of the trap of labour intensification occurs, but into an increasing energy requirement for agriculture, and a declining energy return on investment (EROI).

Despite the limited number of case studies, the Boserupian theory of agricultural development as synthesized in Sieferle's theory of sociometabolic regime transitions give adequate guidance to interpret our findings. In contrast to Boserup's continuous developmental process from a foraging mode to intensive agriculture, our findings comply better with the assumption of qualitative transitions between foraging, the — pre-industrial — agrarian mode and finally fossil- fuelled intensive agriculture. These transitions reflect themselves in a number of sociometabolic indicators, and particularly in labour time. Labour time is low with foragers, rises substantially with agricultural colonization and then with each step of intensification, but can in a next transition be lowered through the use of fossil fuels. However, the pressure on the environment (at least in terms of anthropogenic mass and energy flows per unit area) rises from one transition to the next.

What can be harvested from these findings for a potential next transition, and potential policies in support of it? The key insight is the systemic character of society-nature interactions. Even seemingly trivial and well-meant interventions may trigger a whole chain of consequences in the sociometabolic system that can be detrimental either to the social or to the ecological balance, or both. Traditional development and aid policies tend to overlook the intricate ties between demography, labour time, land degradation and subsistence / income. Which pathways are viable, and which will be beneficial in the long term, needs a thorough consideration leading to maybe very different conclusions for different socioecological systems. Classical sectoral planning to boost the efficiency of one variable alone (such as increasing land productivity or enhancing dairy output) will in effect lead to an overall system change, some of which may not be desirable or sustainable in the long run. Development policies must therefore be sensitive to these systemic interrelations and the trade-offs involved therein.

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Endnote

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2 For a recent review of the lasting impact of Boserup's work, see (Turner & Fischer-Kowalski 2010)

3 Several studies have documented a massive decline in EROI when moving from traditional to industrial agriculture (e.g. Pimentel, et al. 1990, Rambo 1984). In the case of Austrian agriculture, the EROI declined from 6:1 in 1830 to 1:1 in the year 2000, mainly due to the heavy inputs of fossil fuels and nitrogenous fertilizers (Krausmann, et al. 2004).

4 Trinket Island was completely destroyed by the 2004 tsunami, and the surviving inhabitants moved to another island. The data presented here is from previous years, though some information on household working time was corroborated after the tsunami.

5 Each of the field surveys resulted in a doctoral thesis covering many more aspects of the communities than selected for this comparative analysis (Mayrhofer-Grünbühel 2004, Ringhofer 2007, Singh 2003).

6 Livestock grazing was estimated and considered as part of the harvest.

7 We have only limited knowledge on how population dynamics is regulated. In Trinket, historically, there were traditional birth control measures in place, while nowadays, the Nicobarese women willingly participate in India's sterilization programme. In the past, excess population tended to settle on other islands not yet inhabited. In Campo Bello, we know from interviews that they complain about having to shorten fallow times because of population pressure (Ringhofer 2010); we assume the strong growth is mainly due to a recent reduction in mortality rates because of improved medical services. For Nalang and Sang Saeng we have no further information.

8 They are even low in relation to the 70 GJ/cap calculated for historical Austrian villages in 1830 (Krausmann 2004)

9 The material metabolic rates amount to more than 5 tons for the historical Austrian villages mentioned (Krausmann 2004).

10 With Trinket, there is a certain definition problem concerning the "key staple food". They do not agriculturally produce any staple food. What the Nicobarese do is collect coconuts, produce copra, and exchange that copra for rice, which is then the staple food they consume. Nevertheless, we treat copra as their staple food. For Campo Bello and Nalang, where there is shifting cultivation, the fallow areas are included in the area of staple food production, as they functionally are indispensable for this mode of production. Labour time for all three agrarian communities in Table 1 encompasses only the time for the production of the staple food, which is rice in the case of Sang Saeng and Nalang, and plantains, rice, manioc and maize in the case of Campo Bello (all products of the shifting cultivation system). Only fossil fuels used in the production process of the staple food are accounted for.

11 Although the inhabitants of Trinket are sedentary, they do not intensively colonize the island's terrestrial ecosystems. Coconut palms grow on the sandy beaches and bear coconut around the age of 10, and remain productive for almost 100 years without much caretaking by humans. The only occasional work is to dig a coconut into the sand at the right season and a convenient place and protect it from pigs for the first few years. The coconuts are "harvested" by letting them fall down and gathering them, or occasionally by climbing the trees and lopping them down. For a long time, the Nicobarese have exchanged these nuts with ships passing by and bartered them for rice. In the absence of rice, they used pandanus and other tubers as a staple food (Singh 2003). Today, copra (dried coconut flesh) has replaced the nuts as exchange. This requires breaking the nuts open, scooping out the flesh, and collecting firewood. This is untypical agricultural work. The only activity that comes close to agriculture is the feeding of the pigs with coconut flesh. However, this feedstuff comprises only 30% of the pigs' diet — the remaining 70% is scavenged in the forest. Furthermore, pork forms an insignificant part of the diet of the Trinket inhabitants (4gms/cap/day), and pigs are being slaughtered almost exclusively for ceremonies and festivals.

12 Paradoxically, a collapse of this system actually occurred: By the end of 2004 a tsunami disrupted the whole region, killing one third of the islanders, breaking Trinket apart and eliminating all coconut palms. The islanders asked us in for help, but our efforts to motivate them to horticultural activities were completely in vain. Instead, the island population lived on Indian State and international aid until now, completely changing its lifestyle towards consuming food from aid programmes and industrial products they buy from their compensation payments (motor cycles, mobile phones, fancy clothing, etc.). It will take a number of years for new coconut palms to bear fruit, and we consider it an unintended field experiment to see how these communities will survive from now on since the aid is terminated.

13 This includes only the direct input of fossil fuels (e.g. for the machines used in the fields). Industrial systems additionally depend on the indirect use of fossil fuels used for the production process of fertilizers and agrochemicals.

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