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ENERGY ANALYSIS OF COFFEE PRODUCTION SYSTEMS: Implications for Environmental and Economic Sustainability

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Abstract. Data from a 10 year Turrialba Costa Rica study is used for an energy use evaluation of organic agroforestry, chemical agroforestry and sun grown coffee production systems. Sun grown coffee had the highest yield but lowest energy use efficiency. Organic coffee had the highest energy use efficiency and thus the highest environmental sustainability. High energy use efficiency results from efficient nutrient recycling by the community of soil organisms that obtain energy from decomposing coffee pulp and chicken manure. An economic analysis including data from a world survey suggests that sun grown coffee generates the highest income. Governments may encourage producers to plant sun grown coffee because high income from abroad helps balance of trade. Organic coffee provides a greater return on investment than sun grown coffee and would be the choice of a local community that wants to avoid using chemical inputs but requires a higher income than that provided by traditional shade grown coffee. Shade grown coffee provides the lowest income of all systems but a higher return on investment than sun coffee. It is attractive for the small scale farmer because of low input requirements. Each of these systems is associated with a different economic hierarchical level: the traditional farm; the local community; the large scale producer or corporation. Maximizing economic sustainability at one hierarchical level precludes maximizing sustainability at other levels.

1. EVOLUTION OF COFFEE PRODUCTION SYSTEMS

Until the late 1940s, coffee in Latin America was grown by the "Traditional" method that is, as an understory bush beneath tall, mixed forest trees. Coffee grown in this type of agroforestry system is "shade-grown coffee". In the early 1950s, there began a movement to modernize coffee production by planting varieties that are more resistant to coffee leaf rust. These varieties were adapted to growing in full sun, and are known as "sun-grown coffee". This system is characterized by increased reliance on high-yielding varieties, and an increase in chemical inputs, pruning, and coffee plant density (Perfecto et al. 1996). However, concerns about soil erosion, pesticides and loss of biodiversity in sun plantations have raised questions about the sustainability of sun grown coffee plantations.

2. OBJECTIVES

Sustainability can be looked at from an environmental or an economic perspective. Environmental sustainability concerns soil erosion, nutrient depletion and chemical pollution. Economic sustainability concerns the balance between monetary gains and losses for the local grower, the local community, and the national economy.

2.1. Objectives

The objectives of this chapter are:

- to compare environmental sustainability of several types of coffee production systems.
- to examine how the source of energy inputs to coffee systems affects economic sustainability at three hierarchical economic levels: local growers, local communities, and the national economy.

3. ENERGY USE EFFICIENCY

All economic production systems including agriculture require inputs to produce outputs. Energy use analysis (Odum and Odum 1981) has been used to determine the efficiency with which input energy in the form of fertilizers, pesticides, and fuel is used to produce output energy in the form of food under different management and environmental conditions (Black 1971, Steinhart and Steinhart 1974, Cox and Atkins 1979, Fluck and Baird 1980, Pimentel and Pimentel 2008, Gelfand et al. 2010). When inefficiently used fertilizers contaminate streams, fertilizers become pollution. When inefficiently used pesticides kill beneficial insects, pesticides become pollution. Because wasted energy becomes pollution, energy use efficiency is useful for evaluating the environmental impact of various agricultural management strategies (Jordan 2016).

3.1 Agroforestry as a thermodynamic system

Determination of energy use efficiency requires conceptualizing production ecosystems as thermodynamic systems that convert input energy into yield or its energy equivalent. There are two types of energy conversions in ecological thermodynamic systems (Giampietro 2004):

- Endosomatic, meaning conversions resulting from energy whose source is within a system. Endosomatic energy dissipates within its system of origin and therefore has no environmental impact.
- Exosomatic, meaning energy subsidies resulting from inputs originating outside of a system. The energy efficiency ratio (energy out/energy in) as an index of sustainability uses only exosomatic energy as an input. Inefficiently used subsidies are a cause of stress for the receiving system (EP Odum et al. 1979). Although sunlight energy originates outside an agricultural systems, it is not a subsidy but rather the energy flux being subsidized.

3.2 Hierarchical Systems

Energy flow in ecosystems and dollar flow in economies can be represented by a series of hierarchical levels, each one embedded in a higher level. As a result, energy that is endosomatic at one hierarchical level can be exosomatic at another level. Three hierarchical levels of coffee production systems examined in this chapter are: traditional agroforestry; organic agroforestry; sun plantation monocultures.

3.2.1 Traditional Agroforestry (Hierarchical level – the traditional farm)

A traditional agroforestry system consists of a subsystem (traditional farm) embedded in the local economic community (Fig. 1). The farm consists of overstory trees, coffee bushes, and the community of soil organisms. An internal loop of energy flow runs from the overstory trees through the soil community to the coffee bushes and back to the overstory trees.

- Endosomatic energy in the agroforestry plots refers to energy conversions linked to physiological processes within the soil-crop system. Sunlight is intercepted by overstory trees and coffee bushes, and is transformed through photosynthesis to biomass of the trees and bushes, and to coffee cherries. Endosomatic energy is transferred from the overstory trees to the soil community by way of litter fall and root sloughing. (Carrillo et al. 2011). Litter and dead roots are the energy source for the community of soil microorganisms that recycle nutrients into the coffee bushes and overstory trees. This feedback maintains the function of the ecosystem. In thermodynamic terms, the system is autocatalytic since the feedback is mediated by a naturally occurring mechanism.
- Exosomatic energy consists of labor for weeding and pruning by local workers to maintain structure of the system. Yield from the coffee bushes becomes exosomatic input to the traditional farm when it is converted to energy emanating from the local workers.

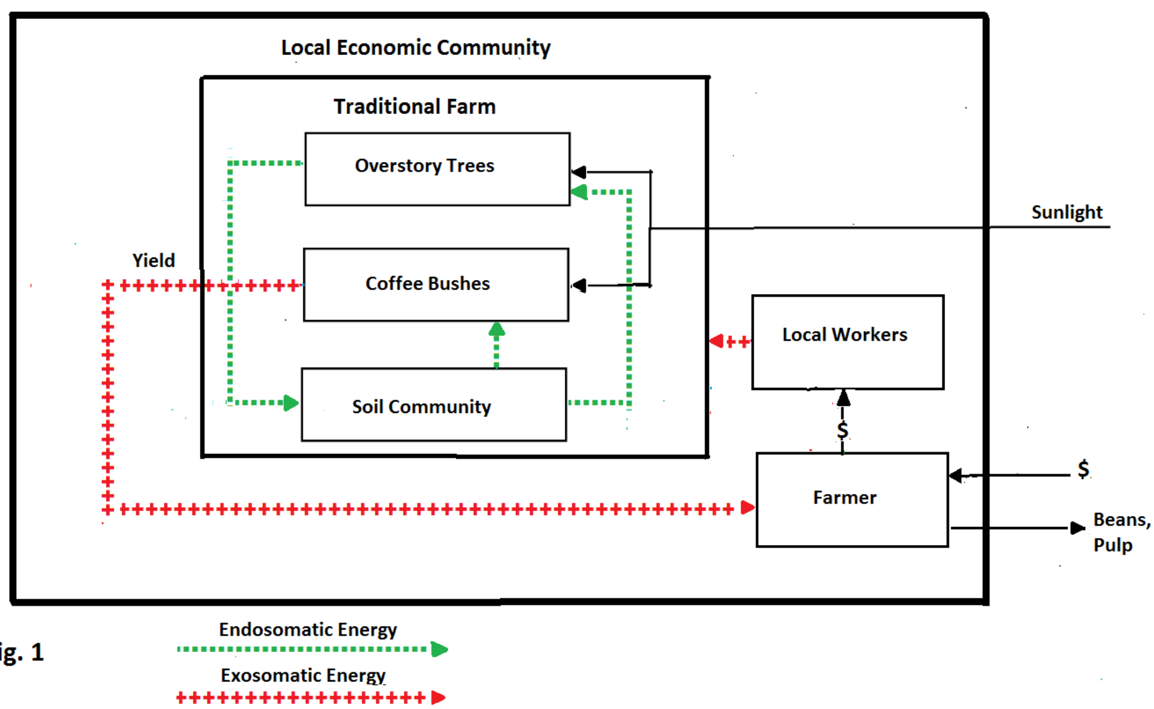

Fig. 1

Fig. 1. Energy flow through a traditional agroforestry coffee production system embedded in a local economic system.

3.2.2 Organic Agroforestry (Hierarchical level - the local economic community)

The organic system (Fig. 2) is a local economic community in which organic agroforestry plots are embedded. A feedback loop consists of money from the sale of coffee beans that is used to pay local workers.

- Yield from the coffee bushes becomes endosomatic energy for the local economic community when part of the yield becomes pulp used as input into the organic plots, and part goes to the farmer to pay workers for separating pulp from beans and for weeding and pruning the agroforestry plots.
- For the organic plots and the local economic community in which the organic plots are embedded, mineral supplements are exosomatic inputs. They originate outside the local community.

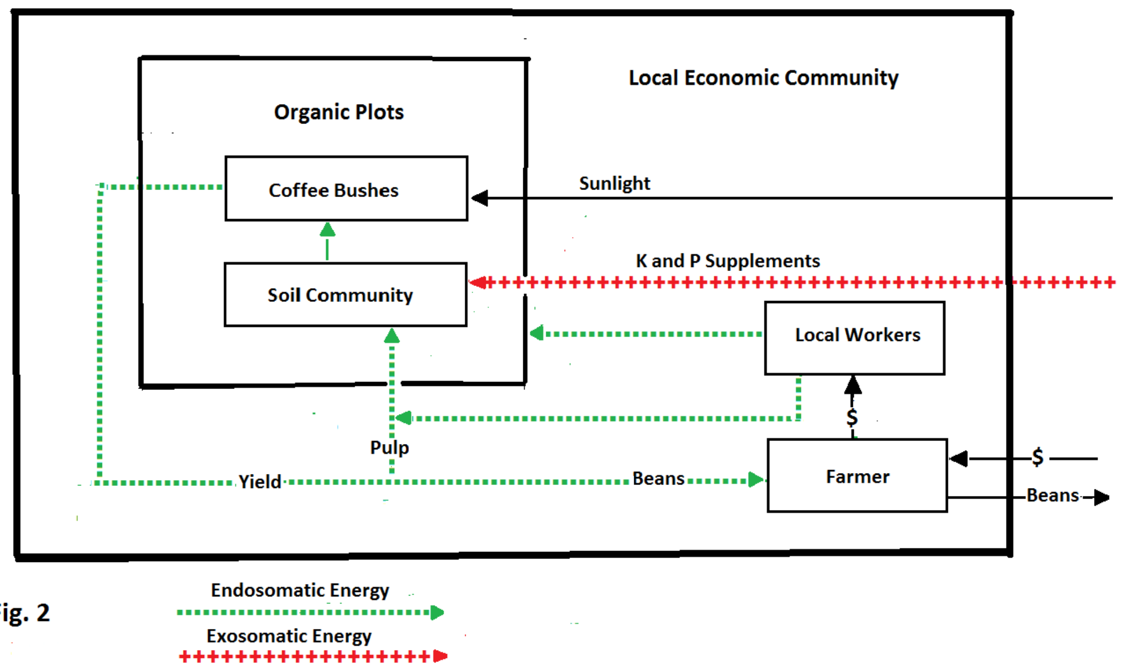

Fig. 2

Fig. 2. Energy flow through a local economic community producing organic coffee.

3.2.3 Sun Coffee Plantation (Hierarchical level – the corporate economy)

Sun coffee plantations represent large scale, industrial type agriculture managed by a corporation or large scale producer (Fig. 3). They are characterized by high energy inputs, and are not really agroforestry systems because all trees and shrubs other than the coffee bushes have been removed. There are no internal feedback loops to produce or sustain nutrient recycling. The corporate economy is closely linked to the national and international economy. The local economic community has little involvement.

- When the beans are sold internationally, yield from the coffee bushes becomes endosomatic energy for the national economy. A feedback loop occurs at the national level.
- Exosomatic inputs include fertilizers, pesticides, fungicides, and petroleum that fuels mechanical cultivation.

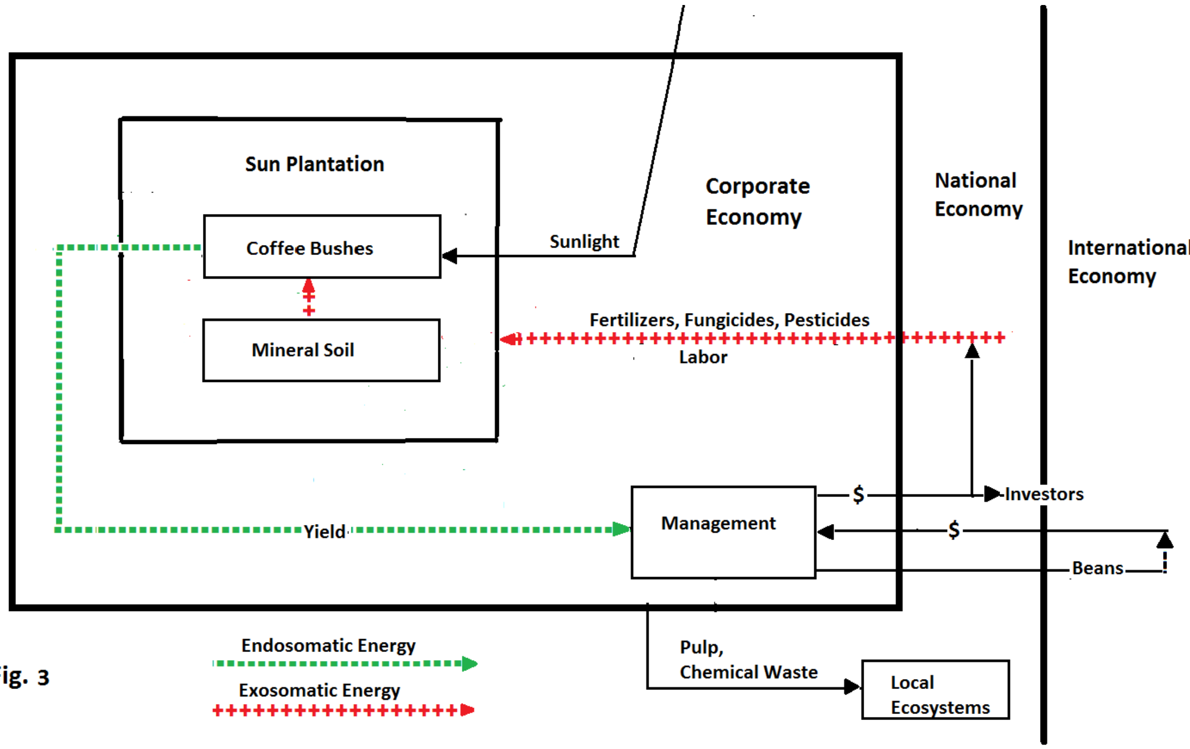

Fig. 3

Fig. 3. Energy flow through a corporate economy that embeds a sun coffee plantation.

4. ENVIRONMENTAL SUSTAINABILITY

A 10-year study comparing five coffee production systems was carried out at Centro Agronómico Tropical de Investigación y Ensañanza (CATIE) Turrialba, Costa Rica beginning in 2000 (Rossi et al. 2011, Virginho Filho et al. 2015). Data from these studies can be used to compare environmental sustainability of the systems, when energy use efficiency is used as an index of environmental sustainability. High energy use efficiency means that a relatively low proportion of input energy goes toward pollution and ecosystem degradation.

4.1 The coffee management study at Turrialba, Costa Rica.

The five systems evaluated in the project were:

- Full sun, intensive chemical fertilization
- Full sun, moderate chemical fertilization
- Agroforestry system, intensive chemical fertilization
- Agroforestry system, moderate chemical fertilization
- Organically managed agroforestry system (coffee pulp and chicken manure for nutrient inputs)

4.1.1. Energy flow through the organic and sun coffee systems

The organically managed agroforestry system (Fig. 2) differed from a traditional agroforestry system (Fig. 1) in an important way. The organic agroforestry research was started in abandoned fields of a sugar cane plantation. The trees that eventually would become overstory were seedlings at the time the experiment started. Thus there was little endosomatic feedback from leaf litter and root decomposition as occurs in traditional systems. Endosomatic feedback in the organic system occurs at the community level, where pulp inputs to the cropping system play the same role as decomposed leaf and root litter in the mature traditional system. The labor to process the pulp and to weed the production plots also is endosomatic energy, since the workers are internal to the local community.

Exosomatic energy in the organic system consists of the potassium and phosphorus supplements. Fuel to run the pulping machine that separates the pulp from the coffee beans also is an exosomatic input, but no data are available. In the sun coffee system (Fig. 3), all energy inputs are exosomatic. Input subsidies in the form of fertilizers are brought in from outside the system to replace the nutrients that are lost due to coffee harvest, nutrient leaching and volatilization. Labor crews are exosomatic when they are hired temporarily for weeding and harvesting. Labor was not measured. While land is often considered along with labor and capital as a factor of agricultural production, land (that is the organic matter content of the soil) is an energy stock, not an energy flow and thus does not contribute to the energy efficiency ratio. However, the stock performs a buffering role, in that the size of the stock on a unit area basis determines the stability of the energy flow.

4.1.2 Energy use efficiency and yield of the organic and sun coffee production systems

Data on nutrient energy inputs from the Turrialba research can be used to compare the energy use efficiency and yield of coffee production systems. The first step is to determine the energy content of nutrient inputs (Table 1).

Type of Input	**Energy Value of Input**
Coffee pulp	12501 Kj/kg (Cubero et al. 2014)
Poultry manure	12052 Kj/kg (Quiroga 2010
Nitrogen fertilizer	42 Mj/kg (Hulsbergen et al. 2001)
Phosphorus fertilizer	15.8 Mj/kg (Hulsbergen et al. 2001)
Potassium fertilizer	9.3 Mj/kg (Hulsbergen et al. 2001)
Total NPK	67 Mj/kg

Table 1. Energy values for fertilizer inputs

The next step is to calculate the nutrient energy input per hectare for the management systems, as in Table 2.

Management type	**Intensity Of Input**	**Gross Input /ha/yr**	**Conversion factor**	**Net Input /ha/yr**	**Energy Content**	**Energy Input /ha/yr**
Chemical (sun monoculture)	High	800 kg fertilizer	10% *	80 kg	67Mj/kg	5.360 Gj
	Medium	400 kg fertilizer	10%*	40 kg	67Mj/kg	2.680 Gj
Organic	Medium	20 T, coffee pulp	10%**	2000 kg	12501 KJ/kg	25.0 Gj
		7.5 T, manure	25%***	1880 kg	12052 KJ/kg	22.6 Gj
		200 kg PO_4	10%**	20 kg	15.8 Mj/kg	0.316 Gj
		200 kg K	10%**	20 kg	9.3 Mj/kg	0.186 Gj
					Subtotal chemical	0.502 Gj
					Sum Organic	48.102 Gj
	Low	½ Medium Input				24.051 Gj

*Assume 10-10-10 fertilizer
**Pulp is 90% water
***Chicken manure is 75% water

Table 2. Energy inputs into the production systems.

For the high intensity chemical systems, input is 5.36 Gj/ha/yr, and for the medium intensity, 2.68 Gj/ha/yr. These are exosomatic inputs. The pulp and manure energy inputs into the organic system are 25.0 Gj and 22.6 Gj respectively. These are endosomatic inputs.
The endosomatic nutrient-supplying pulp and manure inputs for the organic system are energetically five to ten times higher than the exosomatic energy inputs for the sun coffee systems. In the sun coffee system, the pulp energy is disposed of into the environmental commons where it can become pollution. In the organic system it is recycled.

Exosomatic nutrient energy input for the organic system is .502 Gj/ha/yr (the subtotal chemical for organic systems in Table 2) is a factor of 10 lower than the exosomatic input for the high intensity chemical system. The low exosomatic input in the organic systems results in relatively high energy use efficiencies. Table 3 gives the yield, and the ratio (coffee yield) / (exosomatic energy input) of these systems. Since the desired output of these systems is coffee beans, not energy, kg of yield is substituted for energy-out in the ratio of energy use efficiency. Systems are ranked top to bottom from highest ratio (most efficient) to lowest ratio (least efficient) from the 10 yr. average data.

1	2	3	4	5	6	7	8
Overstory species	Management	Chemical Energy Input (Gj/ha)	Yield in 2007 Kg/ha x 10^3	Energy use efficiency * col.4/col.3	Yield, 10 yr. average Kg/ha x 10^3	Energy use efficiency* col. 6/col. 3	Rank
Erythrina poeppigiana	Organic – Low Intensity	.251	8.300	20.2	1.437	5.72	1
Erythrina poeppigiana	Organic – Med. Intensity	.502	8.000	9.76	1.840	3.66	2
Terminalia amazonia	Organic – Low Intensity	.251	3.800	9.27	.892	3.55	3
Terminalia amazonia	Organic – Med. Intensity	.502	11.700	14.27	1.680	3.35	4
Full sun monoculture	Chemical – Med. Intensity	2.680	13.700	5.27	1.921	.72	5
Erythrina poeppigiana	Chemical – Med. Intensity	2.680	6.100	2.28	1.407	.53	6
Terminalia amazonia	Chemical – Med. Intensity	2.680	7.900	2.95	1.321	.49	7
Erythrina poeppigiana	Chemical – High Intensity	5.360	11.700	2.18	2.387	.45	8
Full sun monoculture	Chemical – High Intensity	5.360	13.800	2.57	2.376	.44	9
Terminalia amazonia	Chemical – High Intensity	5.360	7.900	1.47	1.826	.34	10

*Exosomatic energy only

Table 3. Yields and energy use efficiencies of the experimental systems.

- Yields: Yields in the full sun monocultures and chemical input agroforestry systems averaged slightly higher than yields in the organic systems. High intensity chemical inputs for non-organic systems resulted in higher yields than medium intensity inputs. There was no yield advantage in chemical agroforestry plots compared with full sun monocultures. Since the trees were newly planted, an advantage may develop as the trees mature.
- Energy Use Efficiency: Energy use efficiency in the organic systems was always higher than that in the full sun and chemical agroforestry systems. The high energy use efficiency of the organic coffee systems suggests that organic systems provide greater environmental sustainability than systems that must import large amounts of fertilizers to maintain production.

The Audubon Society Shade-Grown Coffee Project (2004) reported that yields from shade grown coffee averaged 550 kg/ha, or about one third the yield of sun grown coffee. Yields from the organic agroforestry systems at Turrialba were considerably higher than world-wide averages for shade grown coffee. Differences are due in part to the quality of feedback from the soil to the plants. The high values for the Turrialba organic plots probably were a result in part of the high nutrient availability in coffee pulp and manure. The nutrient availability in organic matter in shade grown coffee is lower, due to the high content of secondary plant compounds that are difficult for bacteria to metabolize.

4.2 Sun coffee following deforestation

The Turrialba plots were established on an abandoned sugar cane plantation, thus levels of soil organic matter were relatively low. When a traditional agroforestry system is cleared to produce higher yielding sun coffee, the bushes can take advantage of the residual organic matter stock in the soil from decomposing humus and the roots of overstory trees. Energy use efficiency will be high for a few years, and exosomatic energy inputs can be low. However, after a few years when this organic matter oxidizes and is not replenished, exosomatic inputs must rise to maintain high yield. Energy use efficiency in the sun plantations will decrease rapidly due to the disappearance of endosomatic energy feedback.

5. ECONOMIC SUSTAINABILITY

An analysis of past and present economic trends cannot predict economic sustainability for coffee production systems. Energy analysis also cannot predict the economic costs and benefits from a particular coffee production system. However, it can always predict which type of system will give the greatest profit (or least loss) from investment, as prices of coffee and cost of inputs vary. (Yield) **/** (energy-input) ratios are constant for a particular environment, and are not affected by economic variables. They can be better indicators of which management system will give the highest net return on investment (profit) for a particular environment. Table 4 and Fig. 4 use yield and energy input data from Table 3 to illustrate how changes in price of coffee and cost of chemical inputs affects income and return on investment (profit/cost) for selected sun, organic, and shade coffee systems. The comparison of sun grown coffee with organic coffee is from data of the Turrialba study. The traditional shade grown and sun grown yield comparison is from world data of the Audubon Society Shade-Grown Coffee Project (2004).

Economic Trend	Manage-ment System	Price/Kg Yield $	Yield Kg/ha x 10^3	Income $ from Units Produced	Energy Cost $/Gj	Energy Input Gj/ha x 10^3	Cost /ha $	Profit/ha $	Profit/ Cost
Coffee	Sun	2	1.921*	3842	3	2.680*	8040	-4198	-
prices	Organic	2	1.840**	3680	3	.502**	1506	2174	1.44
going up	Sun	5	1.921	9610	3	2.680	8040	1570	0.20
	Organic	5	1.840	9200	3	.502	1506	7694	5.11
Turrialba	Sun	10	1.921	19210	3	2.680	8040	11170	1.39
	Organic	10	1.840	18400	3	.502	1506	16894	11.22
Coffee	Sun	2	1.600	3200	3	2.680	8040	-4840	-
prices	Shade	2	550	1100	3	.502	1506	-406	-
going up	Sun	5	1.600	8000	3	2.680	8040	-40	-
	Shade	5	550	2750	3	.502	1506	1244	0.83
World	Sun	10	1.600	16000	3	2.680	8040	7960	0.96
average	Shade	10	550	5500	3	.502	1506	3994	2.65
Input	Sun	5	1.921	9610	1	2.680	2680	6930	2.59
costs	Organic	5	1.840	9200	1	.502	502	8698	17.33
going up	Sun	5	1.921	9610	3	2.680	8040	1570	0.20
	Organic	5	1.840	9200	3	.502	1506	7694	5.11
Turrialba	Sun	5	1.921	9610	6	2.680	16080	-6470	-
	Organic	5	1.840	9200	6	.502	3012	6188	2.05
Input	Sun	5	1.600	8000	1	2.680	2680	5320	1.99
costs	Shade	5	550	2750	1	.502	502	2248	4.48
going up	Sun	5	1.600	8000	3	2.680	8040	-40	-
	Shade	5	550	2750	3	.502	1506	1244	0.83
World	Sun	5	1.600	8000	6	2.680	16080	-8080	-
average	Shade	5	550	2750	6	.502	3012	-262	-

*Data from full sun monoculture, medium chemical intensity plot in Table 3 (10 yr. average).
**Data from *Erythrina poeppigiana*, organic medium intensity plot in Table 3 (10 year average).

Table 4. Income per hectare and return on investment (profit/cost) of sun, organic, and shade coffee as a function of coffee price and input costs.

Price per Kg yield of coffee beans times yield in Kg per hectare equals income per hectare. Chemical energy cost times chemical energy input per ha gives exosomatic energy cost per hectare. Chemical energy input costs for world average sun and shade were taken to be the same as for sun and organic in the Turrialba study. Profit per hectare is income minus costs. Profit/cost indicates a farmer's net return on investment.

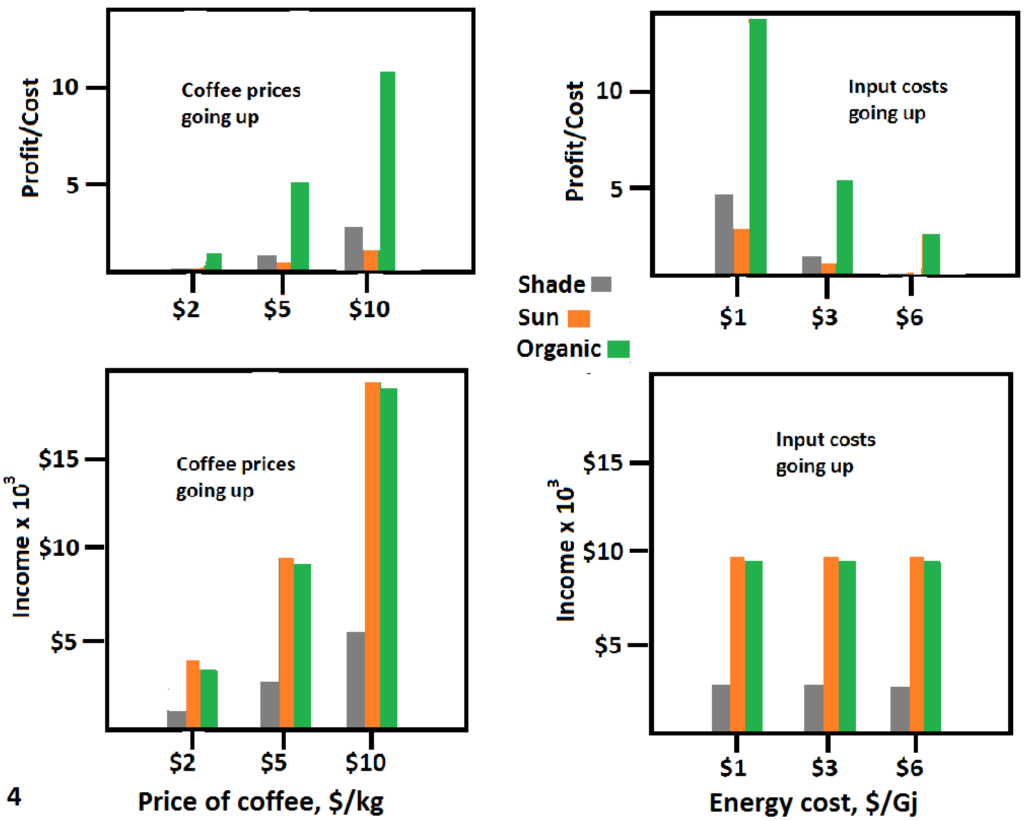

Fig. 4

Fig. 4. Changes in income and return on investment (profit/cost) for sun, organic, and shade coffee systems as coffee prices increase and as costs of inputs to the production system increase.

Indicated values for price of coffee and costs of input are arbitrary. They do not necessarily reflect prices and costs at any point in time. They are used only to show how income and profit are affected by trends in prices and costs. Substituting other values will change income and profit, but will not change trends.

5.1 Economic trends

In both the Turrialba and world average data sets, sun grown coffee always produced the greatest income regardless of prices or costs because sun coffee produced the greatest yield. However, organic and shade coffee always had a higher profit/cost ratio (net return on investment) than sun grown coffee, since costs were always lower for shade and organic coffee.

5.2 Effect of energy sources on economic factors

5.2.1 *When the main source of energy for the coffee production system is within the production plot itself.* This is the case for traditional agroforestry systems, where feedback energy comes from leaf and root litter of the overstory trees. Characteristics of the system are: relatively low production; relatively low opportunity for local labor; relatively low support for the local community and local economy; low income but high return on investment.

5.2.2 *When the main source of energy for the coffee production system is within the local community.* This is the case for the organic production system, where feedback energy comes from local labor, and the coffee pulp and chicken manure that have their source within the local community. Characteristics of the system are: relatively high production; high opportunity for local labor to collect, process, and spread inputs; relatively high support for the local community and local economy; income close to that of sun systems, but higher return on investment.

5.2.3 *When the main source of energy for the coffee production system is outside the local community.* This is the case for sun coffee. Fertilizer inputs come from outside the local community. Characteristics of the system are: high production; low opportunity for local labor; low support for the local community and local economy; high income but low return on investment.

5.3 Feedback and sustainability

Internal feedback of endosomatic energy determines the sustainability of each hierarchical level. The traditional agroforestry system has nutrient cycling feedback within the plot itself. It is autocatalytic and thus its environmental sustainability is high. It would be the choice for an individual farmer having little capital. Organic coffee also is autocatalytic. It optimizes local economic sustainability through the energy feedback loop provided by local workers, and environmental sustainability through the nutrient feedback provided by pulp. Sun coffee would be the choice of a government wanting to increase exports to improve international balance of payments. However the sun coffee system has no autocatalytic feedback that maintains environmental sustainability.

CONCLUSIONS

6.1 Environmental sustainability

Energy use analysis shows that traditional and organic coffee production systems are more environmentally sustainable than sun grown systems because of the presence of internal energy recycling loops. Internal recycling builds up stocks of soil organic matter that nourish soil micro-organisms.

6.2 Economic sustainability

The profit/cost ratio determines the economic sustainability of each hierarchical level. The degree of sustainability depends on the relative contributions of “free” endosomatic energy and energetically expensive exosomatic energy. Shade grown coffee has a high proportion of endosomatic energy, and thus promotes sustainability for the local grower. Organic coffee also has a high proportion of endosomatic energy, and thus promotes economic sustainability for the local community. There are no endosomatic energy feedbacks within the corporate sun system. Sustainability depends on low costs of exosomatic inputs and high international coffee prices.

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