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Interface ecosystems with an oil spill in a Venezuelan tropical savannah

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Abstract

Frequent oil spills associated with oil operations in tropical savannas are developing new ecosystems that may be symbiotic interfaces between industry and environment. This paper describes these developments, the role of restoration efforts and uses 'emergy' to evaluate the changes. In April 1991, an estimated 36 000 barrels (5724 m^3) of 40 gravity crude oil were released into 4600 ha of tropical grassland-scrub and palm swamp communities from the blowout of a Venezuelan Oil Company well (Corpoven MUC-21) in Monagas State in eastern Venezuela. Ecologic and economic impacts of the oil spill were estimated using emergy analysis. The oil spill, its damages, and subsequent clean up were evaluated by comparing the emergy flows associated with each aspect of the spill and ecological restoration. Using emergy measures of solar emjoules (sej) and converting to macro-economic dollars (emdollars), total damages (including cleanup and spilled oil) amounted to 48.5 E18 sej or 11.3 E6 US emdollars. Environmental damages to ecosystems and agro-ecosystems amounted to about 22% of the total, while economic losses and costs of restoration were about 78% of the total. The area affected by spilled oil was divided into four zones based on post spill treatments and amount of spilled oil. The largest ecological impact was to a lightly oiled zone (about 4500 ha) but was relatively short lived having recovered ecological productivity (GPP) within 30 days. A zone where heavily oiled soil was removed (9 ha) and a third zone where heavy surface oil was burned (80 ha) made up a smaller fraction of total losses. The zone with soil removal was estimated to require about 15 yrs to recover, while the area that was burned was estimated

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to recover in about 10 yrs. A fourth zone that was heavily oiled but received no further treatments (11 ha) exhibited the smallest total losses and recovery was estimated to require only 5 yrs. A method is suggested for evaluating the benefit/cost ratio of ecological restoration projects using the four zones for comparative purposes.

Keywords: Emergy analysis; Oil spill; Ecological restoration

1. Introduction

An area of ecological engineering is the restoration of drastically altered landscapes following human induced changes. Oil spills in both terrestrial and marine environments represent interesting studies in the amount and timing of restoration efforts. Left alone, most oil spill areas will recover in time, thus the degree of restoration activity should be a function of measured benefits. For instance, one benefit may be the fact that ecological productivity will be restored faster with restoration than if no restoration is attempted. A benefit/cost analysis could be conducted using the productivity gain as benefit compared to restoration costs. To be effective, it might be assumed that costs would not exceed benefits. In this way, the degree of restoration could be modeled to obtain maximum benefits with minimum inputs.

Measuring benefits and costs across landscape systems that include economic payments, energy flows, human labour and ecological productivity requires a system of evaluation that can express these various ‘forms’ of energy in units of the same type. Emergy analysis (Odum, 1996) is a method of analysis that can express all flows of energy, materials, and economic inputs in common units; the amount of energy required to make them. In this study both the economic costs (including oil spill control, cleanup activities, and monitoring and restoration assessment) and environmental impacts caused by an oil spill in a tropical savannah of eastern Venezuela (Fig. 1) were evaluated using emergy analysis. Perspectives on the appropriate amount of restoration activity were addressed using the premise that restoration should yield a net benefit to society.

1.1. Chronology of events

On April 8, 1991, the oil well, MUC-21, belonging to Corpoven, S.A. (branch of Venezuelan Oil Company -PDVSA-), began to release pressure due to a failure in its top valves. Within a few hours, pressures of around 1500 psi, caused a blowout of gas, light oil and condensed hydrocarbons. An estimated 36 000 barrels (5724 m^3) of 40 gravity crude oil from the blowout of the well were released into about 4600 ha of tropical grassland-scrub and palm swamp communities.

The Local Contingency Plan of Corpoven was activated on the same day. Oil workers and members of the Army National Guard were deployed to the site carrying equipment to control and prevent overland flow of the oil spill into a swamp palm forest (called 'Morichales') and eventually into a nearby river. The oil well structure received severe damage complicating its repair and termination of the

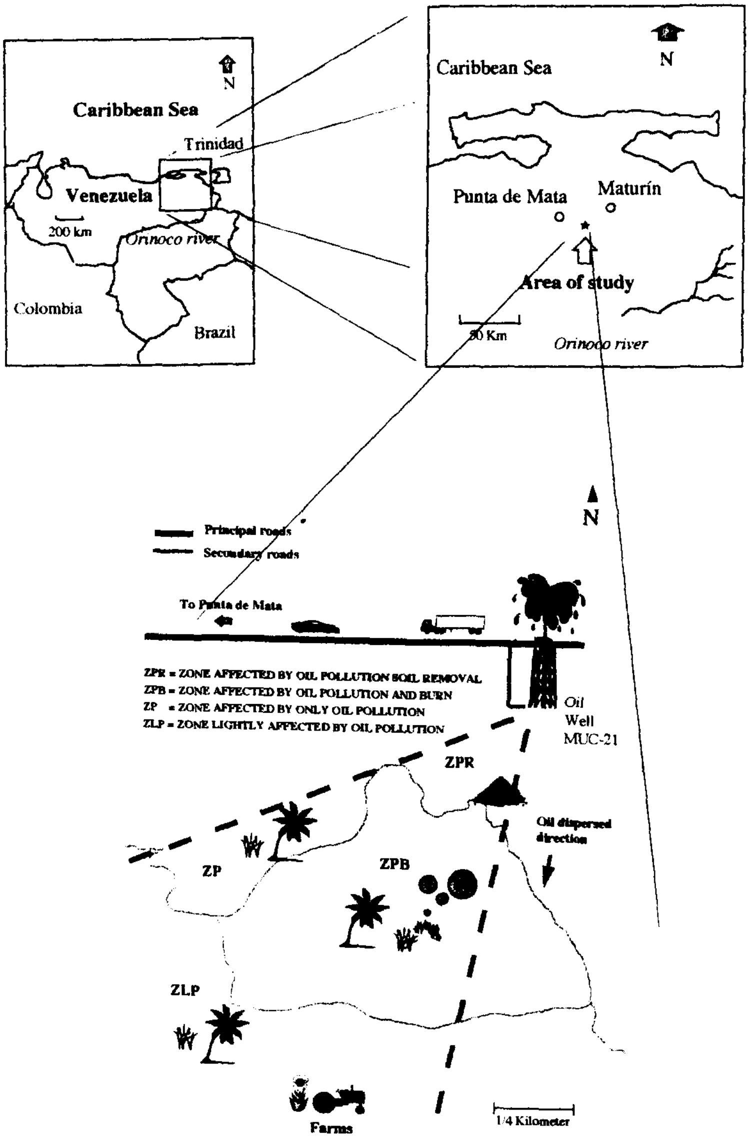


Fig. 1. Map showing the location of the MUC-21 oil spill, zones of heavy oiling (ZP, ZPB, and ZPR) and the zone of light oiling (ZLP). Area of ZPR was about 9 ha, ZPB was about 80 hectares, and ZP was about 11 ha. The area of ZLP was about 4500 ha.

source of gas and spray oil. The immediate installation of oil net controllers, skimmers, absorbent materials and loam, as well as, the construction of channel-dams for collection of oil and the use of vacuum trucks, stopped the overland flow of the oil prior to its entrance into the river.

After 11 days the well head was completely closed. However, the oil spray contaminated more than 4600 ha of savannah and palm forests. One hundred hectares received a dose of 4–5 l/m^2 and 4500 ha received less than 1 l/m^2. In total, the oil spray reached approximately 27 000 ha of the downwind landscape but had negligible impact in this wider area.

At the end of April, a zone nearest the oil well was deforested and almost 9 ha of contaminated soil (top stratum between 0–30 cm deep) was removed. More than 25 000 m^3 of soil were removed, transported, and deposited in assigned areas used as waste yards. In addition, on the third week of May a shrub fire, usually present in the dry season (from January to May), caused a destructive burn over another portion of the contaminated zone surrounding the well. Totalling about 80 hectares of savannah and palm forest, the fire burned all remaining vegetation.

In August of 1992, INTEVEP, S.A. began evaluating the reclamation of ecological processes through mapping, soil characterization, hydrocarbon monitoring, physiological vegetation measurements, and revegetation. At the end of 1992, recovery of soil biological activity was evaluated by measuring edaphic respiration, enzymatic activities and nutrient mineralization for a period of 2 yrs.

1.2. Plan of Study

As a result of the 'treatments' (soil removal, burning and a control area not restored) the spill provided the opportunity to study self organization and compare it with intensive technological efforts at restoration. The emergy values (emvalue) of economic effects and ecologic damages were evaluated using common units of solar emergy. Ecologic damages included both biomass mortality and loss of gross primary production (GPP) for the recovery period. Emvalue of economic effects included: the value of the spilled oil, payments to farmers and the economic costs of clean up and restoration activities. First, damages were evaluated for each of the four zones: zone of pollution and soil removal (ZPR), zone of pollution and burning (ZPB), zone of pollution only (ZP) and the zone that was lightly polluted (ZLP). Second, economic costs of clean up and restoration activities were evaluated in emergy for each zone, and compared with ecological damages. Finally, to develop an emergy benefit/cost analysis, the benefit of restoration was expressed as the difference between 'natural self-organization' and self-organization that resulted from cleanup and restoration. In effect, restoration should increase the self-organizational process, thus decreasing the time required to reach levels of productivity characteristic of the landscape prior to the spill.

2. Methods

Brief field methods and laboratory techniques of analysis as well as methods for emergy analysis are given here. For complete field and laboratory methodology see Prado et al. (1994b). A complete description of the emergy analysis methodology may be reviewed in a recent text by Odum (1996).

2.1. Field and laboratory data

2.1.1. Petroleum concentration in soil

Crude oil concentration was sampled by gravimetric measurement of total hydrocarbon extracted from selected soil samples. This value was obtained by weighing 50 g of oiled soil sample, followed by the addition of 15 ml of methanol for water removal and then extracted with 30 ml of dichloromethane in contact for 10 min. The extract was separated by vacuum suction and double rotaevaporation using 2 or 3 ml of benzene.

2.1.2. Biomass

Vegetation plots were established in the grasslands for aerial measurement of biomass. Vegetation biomass was collected in both the dry and wet season, and yearly average standing biomass calculated. Collected material was separated, dried at 50–55°C for 72 h and weighed. Literature values were used to estimate biomass of palm swamps (Golley et al., 1988; Gonzalez-Boscán, 1990; Myers, 1981).

2.1.3. Estimation of revegetation time

The oil spill area was classified according to the various ‘treatments’, or zones where oil cleanup was conducted differently (Fig. 1). Each zone was studied separately after the spill and restoration activities for 2 yrs and compared to control areas not affected by oil spill (Prado et al., 1994b).

Vegetation recovery was documented by monitoring plant community composition (taxonomy, percent cover, changes in biomass, successional trends), photosynthetic activity (based on the CO_2 consumption through infrared gas analysis) and stomata movement (taken as water vapour resistance measured on the leaves). Trends in the soil community recovery were evaluated by enzymatic activities (assays of phosphatase and urease activity), C, N, and P mineralization (measured by incubation processes) and soil respiration (measured as CO_2 soil production trapped in KOH 1 M solution). These trends were plotted as graphs and recovery time estimated by straight line projection to values characteristic of control areas.

2.2. Emergy analysis

Emergy analysis is a method of energy analysis that accounts for the direct and indirect use of energy in producing a commodity, resource, fuel, or service, in energy of one form (usually solar emergy). The solar emergy in a resource, product, or service is the sum of the solar energies required to make it. Emergy includes both fossil fuel energies and environmental energies (like sunlight, rain, tides, etc.) that are necessary inputs to most processes of energy and material transformation. Emergy analysis differs from economic analysis because instead of using the dollar value of goods, services, and resources to determine value, a measure of resource quality is used.

Definitions

Energy	Sometimes referred to as the ability to do work. Energy is a property of all things which can be turned into heat, and is measured in heat units (BTUs, calories, or joules).
Emergy	An expression of all the energy used in the work processes that generate a product or service, in units of one type of energy. Solar emergy of a product is the energy of the product expressed in equivalent solar energy required to generate it. Sometimes its convenient to think of emergy as energy memory.
Emjoule	The unit of measure of emergy, or emergy joule. It is expressed in the units of energy previously used to generate the product; for instance the solar emergy of wood is expressed as joules of solar energy that were required to produce the wood. Solar emjoules is abbreviated to 'sej.'
Emdollar (or EM$)	A measure of the money that circulates in an economy as the result of some process. In practice, to obtain the macroeconomic dollar value of an emergy flow or storage, the emergy is multiplied by the ratio of total emergy to Gross National Product for the national economy.
Transformity	The ratio obtained by dividing the total emergy that was used in a process by the energy yielded by the process. Transformities have the dimensions of emergy/energy (sej/J). A transformity for a product is calculated by summing all of the emergy inflows to the process and dividing by the energy of the product. Transformities are used to convert energies of different types to emergy of the same type.

2.3. Emergy evaluation of ecologic damages and economic costs

For a complete description of the methods employed to evaluate the damages and economic effects the reader is referred to several publications (Odum, 1978, 1984, 1986, 1996). In general, the methodology evaluates the main flows of resources, energy, and human services within a study region for the period of interest and converts them into common units of emergy using transformities. Standard global transformities were used for rain and ground water (Odum, 1996). Transformities for biomass and GPP for the various ecosystems affected by the oil spill were calculated as part of this study (given as Appendix A), and the transformity for fuel, based on data from Odum (1996). The transformity for human service was calculated for the Venezuelan economy directly, using the ratio of gross domestic product (GDP) to total emergy flow in the economy. An emergy evaluation of the Venezuelan economy is given as Appendix B.

The emergy analysis begins with the construction of an energy systems diagram. Energy systems diagrams of the system (region) of interest are drawn to organize thinking and determine pathways, interactions, and storages that are likely to be affected. System diagrams help to identify causality and provide a convenient means of inventorying impacts. Each pathway or storage in the diagram that changes is evaluated in an emergy analysis table.

2.4. Emergy analysis tables

To evaluate the impacts of the oil spill and compare restoration efforts with their net result, an emergy analysis table was constructed based on the systems diagram. Each pathway and storage in the systems diagram that changes was evaluated first in the actual units of change, then multiplied by its transformity to yield emergy. The emergy analysis table is organized with the following headings:

1 Note	2 Item	3 Raw Units	4 Transformity	5 Solar Emergy	6 Emdollars
Row 1					
Row 2					
Row ...					

Each row in the table is an inflow or outflow pathway or pathway that changed in the aggregated systems diagram; pathways are evaluated as fluxes in units per year. Six columns describe each pathway as follows:

Column 1	(note)	The line number for each pathway, and corresponding footnote number that contains sources and calculations for the item.
Column 2	(item)	The item name that corresponds to the name of the pathway in the aggregated systems diagram.
Column 3	(raw units)	The actual units of the flow, usually evaluated as flux per year. Most often the units are energy (J/year), but sometimes are given in g/year or dollars/year.
Column 4	(transformity)	Transformity of the item.
Column 5	(solar emergy, sej)	The product of the raw units in column 3 and the transformity in column 4.
Column 6	(emdollars)	The result of dividing solar emergy in column 5 by the emergy:money ratio (calculated independently) for the economy of the nation within which the system of interest is embedded.

Emergy equivalents of the items of change (biomass, GPP, human service, fuels, and goods) were calculated using methods described in Odum (1996). First the units of each form of energy (biomass, g OM/m^2; GPP, g OM m^{-2} yr^{-1}; human service, dollars; fuel, J/yr; goods, dollar value) were calculated from the field data. Grams of organic matter were converted to energy using standard conversions (see Appendix A). These are entered in column 3. Then units of energy (or dollars) were multiplied by their respective transformities (column 4) to obtain their emergy equivalents (column 5). Finally, emergy was divided by the ratio of total emergy use/dollar, characteristic of the economy, to yield the emdollar value of the actual item of change (column 6).

2.5. Emergy evaluation of net benefit of restoration

The benefit of restoration activities was evaluated based on the premise that restoration should result in faster recovery of the affected ecosystems than would occur if the restoration was not conducted. Emergy equivalents of the recovery and restoration activity allows their direct comparison as the benefit (emergy value of the difference between recovery with and without restoration) and the cost (emergy value of restoration).

Recovery was calculated as the emergy equivalent of GPP. Graphs were constructed, based on field data, of recovery of GPP with and without restoration for each of the treatments, and the difference between the two lines (the area) was the emergy value of benefit between restoration and no restoration. An emergy benefit/cost ratio was then calculated.

3. Results and discussion

The combined regional system that was affected by the oil spill is diagrammed in Fig. 2. The renewable driving energies, purchased goods and services, and internal storages and processes are shown. Numbered pathways in the diagram refer to rows in the energy analysis table (Table 1). The system boundaries included the underground storage of oil, shown as the central storage in the diagram. Oil was extracted and transported from the region, but in the process accidental release resulted in spilled oil. In the cleanup following the spill, oil was removed directly, carried out with soil, and burned. In some areas, where oil remained in place, the oil will be broken down in time and recycled through organic matter pathways.

Ecological and agricultural impacts from the spilled oil included mortality of biomass, and annual gross primary production that was lost during system recovery. Also, some contaminated soil was removed; thus soil organic matter was carried off and lost from the region. Economic costs included payment to farmers for lost crops, and the economic value of the oil. Also included as economic costs were the purchased goods and services for cleanup and restoration.

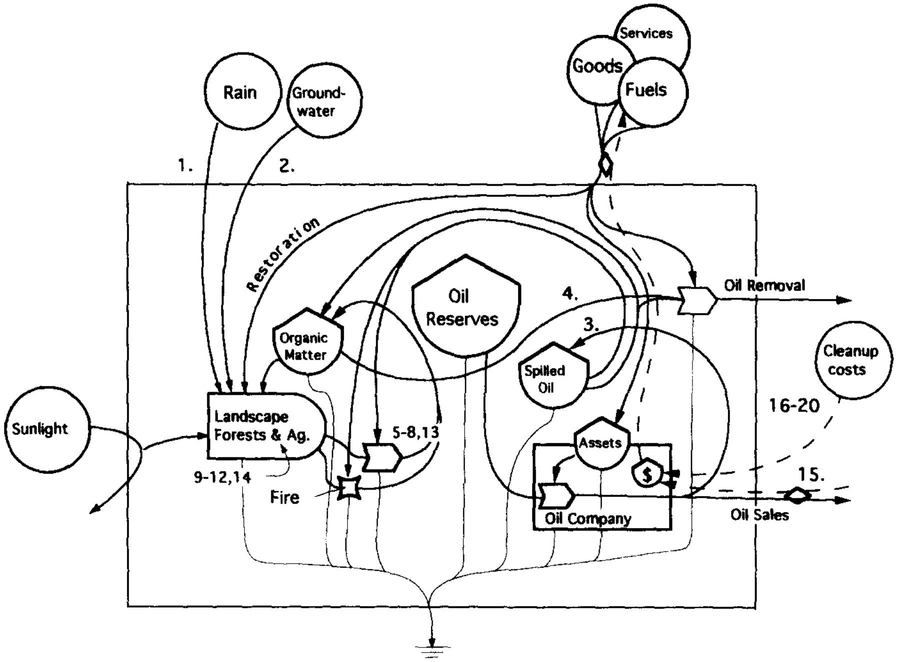


Fig. 2. Energy systems diagram of the savannah system showing ecological systems, oil reserves, spilled oil, and the flows of goods and services used in cleanup and restoration. Numbers on pathways refer to items in Table 1.

3.1. Emergy analysis of oil spill

Emergy flows in the oil spill region are summarized in Table 1. The flows were calculated for a 15-yr period; the time estimated for the region to fully recover from oil spill damages (Gonzalez-Boscán, 1990; Prado et al., 1994b). All values in the table are expressed first in units of energy or currency, then transformed into solar emergy in the fifth column. In the final column, all emergy flows are expressed in emdollars by dividing emergy in column 5 by the emergy/currency ratio for Venezuela (5.18 E12 sej/$, calculated from an emergy analysis of the Venezuelan economy as summarized in Appendix B).

Renewable emergy inflows result from the chemical potential energy of rainfall and groundwater (rows 1 and 2). Their total contribution to the oil spill area for the 15-yr period was 138.7 E18 sej. The spilled oil represents a non-renewable emergy inflow (row 3), the value of which was 9.9 E18 sej.

Items 4 through 14 are the natural resource losses in the various zones. Each zone has two different losses: biomass mortality, and lost GPP during the period of recovery. The largest loss (row 8) was biomass in the zone that was lightly contaminated (ZLP), equal to 7.4 E18 sej. While the impacts were only minor

Table 1
Summary of emergy flows in the region of the oil spill at Punta de Mata, Monagas State, Venezuela (over a 15 year period)

Note	Item	Value	Units	Transformity (sej/unit)	Solar emergy (E18 sej)	Emdollar value (E6 U.S. Em$)
	RENEWABLE ENERGY INFLOWS					
1	Rain (chemical potential)	1.89E+15	J	15423 (a)	29.2	5.5
2	Ground water	3.55E+15	J	30846 (b)	109.5	20.5
	Subtotal Renewable Emergy Inflows				138.7	26.0
	NON-RENEWABLE ENERGY FLOWS					
3	Oil spill	1.83E+14	J	54000	9.9	1.9
	NATURAL RESOURCE LOSSES					
4	Organic matter in ZPR	1.75E+13	J	73750 (a)	1.3	0.2
5	Biomass in ZPR	3.26E+12	J	45500 (b)	0.1	0.03
6	Biomass in ZPB	2.89E+13	J	45500 (b)	1.3	0.3
7	Biomass in ZP	1.99E+12	J	45500 (b)	0.1	0.02
8	Biomass in ZLP	1.63E+14	J	45500 (b)	7.4	1.4
9	Productivity ZPR	1.19E+14	J	2080 (b)	0.2	0.05
10	Productivity ZPB	6.33E+14	J	2080 (b)	1.3	0.3
11	Productivity ZP	4.83E+13	J	2080 (b)	0.1	0.02
12	Productivity ZLP	3.28E+14	J	2080 (b)	0.7	0.1
13	Agriculture biomass	5.27E+12	J	52000 (b)	0.3	0.1
14	Agriculture production	4.52E+13	J	102000 (b)	4.6	0.9
	Subtotal Natural Resource Losses				17.5	5.3
	ECONOMIC SYSTEM LOSSES					
15	Oil spilled	6.30E+05	$	5.18E+12 (c)	3.3	0.6
16	Oil well structure	2.10E+06	$	5.18E+12 (c)	10.9	2.1
17	Oil cleanup operation	1.38E+06	$	5.18E+12 (c)	7.1	1.4
18	Payments	7.50E+05	$	5.18E+12 (c)	3.9	0.8
19	Reclamation cost	5.90E+05	$	5.18E+12 (c)	3.1	0.6
20	Top soil removing	5.40E+05	$	5.18E+12 (c)	2.8	0.5
	Subtotal Economic Costs	5.99E+06	$		31.0	6.0
	Total losses (sum 4-14 and 15-20)				48.5	11.3

Transformities from: Odum, 1996 (a), Appendix A (b), Appendix B (c)

Footnotes to Table 1

1 RAIN CHEMICAL POTENTIAL ENERGY

Area =	5.10E+07	m2	Field data
Rainfall rate =	1.002	m/yr	Prado et.al, 1994a
Runoff =	50%		Assumed by runoff
Rainfall used by plants =	0.501	m/year	
Gibbs No =	4.94E+03	J/kg	Odum, 1996

Rain chemical potential =	(5.1E+07m2)(501m/year)(1000kg/m3)(4940J/kg)*15year		
Energy value of rain =	1.89E+15	J	

2 GROUNDWATER

Water used by the plants as evapotranspiration.

Rainfall in the zone =	1.002	m/yr	Prado et.al, 1994a
Rainfall used by plants =	0.501	m/yr	Assumed by runoff
Ave. regional Evapot. =	1.440	m/yr	Sarmiento, 1984
Gd.water used by plants =	0.939	m/yr	Regional Evapotranspiration
Area =	5.10E+07	m^2	Field data
Groundwater =	(5.1E+07m^2)(0.939m/year)(1000kg/m^3)(4940J/kg)*15year		
Energy value of gd. water =	3.55E+15	J	

3 OIL SPILLED

Oil flowed =	3.60E+04	barrels	Prado et.al, 1994a
	5.72E+06	liters	
Oil recovered =	6.00E+03	barrels	Prado et.al, 1994a
	9.54E+05	liters	
Oil spilled =	3.00E+04	barrel	Field data
	1 Barrel = 6.1E+09 Joules Cook, 1979		
Losses	(3.00E+4 barrels)(6.1E+09Joules/barrel)		
Energy value of oil =	1.83E+14	J	

4 ORGANIC MATTER AFFECTED BY TOP SOIL REMOVAL (ZPR)

Zone affected by oil spill and top soil removal

Area removed =	9.00E+04	m^2	Field data
Soil depth =	3.00E-01	m	Field data
Density =	1.43E+06	g/m^3	Casanova, 1991
Organic matter =	2%		Field data
	1.0 g Org. M. = 5.4 Kcal		Odum, 1996
	1 Kcal = 4186 Joules		
Grade of damage =	100	%	
Energy value of O.M. =	(3.86E+10g)(0.02)(5.4Kcal/g)(4186J/Kcal)		
=	1.75E+13	J	

5 BIOMASS IN ZONE AFFECTED BY POLLUTION AND SOIL REMOVAL (ZPR)

Area removed =	9.00E+04	m^2	Field data
Biomass average =	2.40E+03	g/m^2	Field data; Golley et.al, 1988
	1.0 g biomass = 3.6 Kcal		Odum, 1996
Grade of damage	100	%	
Energy value of biomass =	(9.00E+04 m^2)(2.40E+03 g/m^2)(3.6 Kcal/g)(4186 J/Kcal)		
=	3.26E+12	J	

6 BIOMASS IN ZONE AFFECTED BY OIL POLLUTION AND BURNING (ZPB)

Area polluted & burned =	8.00E+05	m^2	Field data
Biomass average =	2.40E+03	g/m^2	Field data; Golley et.al, 1988
	1.0 g biomass = 3.6 Kcal Odum, 1996		
Grade of damage	100	%	
Energy value of biomass =	(8.0E+05 m^2)(2.40E+03g/m^2)(3.6 Kcal/g)(4186 J/Kcal)		
=	2.89E+13	J	

7 BIOMASS IN ZONE AFFECTED ONLY BY OIL POLLUTION (ZP)

Area polluted = 1.10E+05 m^2 Field data
Biomass average = 2.40E+03 g/m^2 Field data; Golley et.al, 1988
1.0 g biomass = 3.6 Kcal Odum, 1996
Grade of damage 50 %
Energy value of biomass = $(1.10E+05\ m^2)(2.40E+03 g/m^2)(3.6\ Kcal/g)(4186\ J/Kcal)*0.5$
= 1.99E+12 J

8 BIOMASS IN ZONE LIGHTLY AFFECTED BY OIL POLLUTION (ZLP)

Area lightly polluted = 4.50E+07 m^2 Field data
Biomass average = 2.40E+03 g/m^2 Field data; Golley et.al, 1988
1.0 g biomass = 3.6 Kcal Odum, 1996
Grade of damage = 10 %
Energy value of biomass = $(4.50E+07\ m^2)(2.40E+03\ g/m^2)(3.6\ Kcal/g)(4186\ J/Kcal)*0.1$
= 1.63E+14 J

9 GROSS PRIMARY PRODUCTION (GPP) AFFECTED IN ZPR

Net primary prod. (NPP) = 1.10E+03 g $O.M./m^{2}*yr$ Myers, 1981
GPP = 5.3 times NPP UNESCO, 1978
GPP = 5.83E+03 g $O.M./m^{2}*yr$
Area affected = 9.00E+04 m^2 Field data
1.0 g biomass = 3.6 Kcal Odum, 1996
Establishment time in grass = 3 years Field data
Establishment time in M. flexuosa = 25-30 years Field data
Average establishment time = 15 years
Energy value of GPP = $(5.83E+03g\ O.M./m^2/yr)(9.0E+04\ m^2)(3.6\ Kcal/g)(4186\ J/Kcal)*\ 15\ yr$
= 1.19E+14 J

10 GROSS PRIMARY PROD.(GPP) AFFECTED IN ZPB

Area polluted & burned = 8.00E+05 m^2 Field data
GPP = 5.83E+03 g $O.M./m^{2}*yr$ See footnote 9
1.0 g biomass = 3.6 Kcal Odum, 1996
Establishment time 9 years Assumed by field data
Energy value of GPP = $(5.83E+03g\ O.M./m^2/yr)(8.0E+05\ m^2)(3.6\ Kcal/g)(4186\ J/Kcal)*\ 9\ yr$
= 6.33E+14 J

11 GROSS PRIMARY PROD. (GPP) AFFECTED IN ZP

Area polluted = 1.10E+05 m^2 Field data
GPP = 5.83E+03 g $O.M./m^{2}*yr$ See footnote 9
1.0 g biomass = 3.6 Kcal Odum, 1996
Establishment time 5 years Assumed by field data
Energy value of GPP = $(5.83E+03g\ O.M./m^2/yr)(1.10E+05\ m^2)(3.6\ Kcal/g)(4186J/Kcal)*\ 5\ yr$
= 4.83E+13 J

12 GROSS PRIMARY PROD. (GPP) AFFECTED IN ZLP

Area polluted = 4.50E+07 m^2 Field data
GPP 5.83E+03 g $O.M./m^{2}*yr$ See footnote 9
1.0 g biomass = 3.6 Kcal Odum, 1996
Establishment time 30 days = 0.083 years **Assumed by field data**
Energy value of GPP = $(5.83E+03g\ O.M./m^2/yr)(4.50E+07\ m^2)(3.6\ Kcal/g)(4186\ J/Kcal)*\ 0.083\ yr$
= 3.28E+14 J

13 BIOMASS IN AGRICULTURE
(fruit, grain & root crops)
Crop biomass average = 7.00E+02 g/m^2 Silva and Moreno, 1993
Area affected = 5.00E+06 m^2
Grade of damages = 10% Field data
1.0 g biomass = 3.6 Kcal Odum, 1996
Energy value of crop biomass = (7.0E+02 g/m^2)(5.0E+06 m^2)(3.6 Kcal/g)
(4186 J/Kcal) * 0.1
= 5.27E+12 J

14 AGRICULTURE PRODUCTION
(fruit, grain & root crops)
Crop prod. average = 1.20E+03 g/m^2*yr Casanova, 1991
Area affected = 5.00E+06 m^2
Production time lost = 0.50 year Field data
1.0 g biomass = 3.6 Kcal Odum, 1996"
Energy value of crop prod. = (1.20E+03 g/m^2/yr)(5.0E+06 m^2)(3.6 Kcal/g)
(4186 J/Kcal) * 0.5
= 4.52E+13 J

15 DOLLAR VALUE OIL SPILLED
Oil flow = 3.60E+04 barrels Prado et.al, 1994a
Oil recovered = 6.00E+03 barrels Prado et.al, 1994a
Oil spilled = 3.00E+04 barrels
Dollar value of Oil = 2.10E+01 $/barrel PDVSA, 1995
Total value of oil = (30000 barrels)(21 $/barrel)
= 6.30E+05 $

16 OIL WELL STRUCTURE
Including equipment, structure and labor for installation
Value losses = 2.10E+06 $ Field data

17 OIL SPILL CLEANUP OPERATION
Cost of equipment used in manual & mechanical cleanup of oil spill
Cost average (8 places) = 2.30E+02 $/barrel Oil Spill Conf. 1987
Oil recovered = 6.00E+03 barrels Prado et.al, 1994a
Value losses = (6000 barrel)*(230 $/barrel)
= 1.38E+06 $

$124000 in ZPR, $1104000 in ZPB and $152000 in ZP

18 PAYMENTS
Damages paid in repair of rural buildings and purchases of land , equipment, crops & etc.
Cost = 1.50E+03 $/ha Field data
Damages = (1500 $/ha)(500 ha)

= 7.50E+05 $

$12000 in ZPR, $17000 in ZPB, $120000 in ZP and $601000 in ZLP

19 RECLAMATION COST
Reclamation costs in monitoring, evaluation, research projects, reforestation & etc.
Monitoring, Evaluation,
& research projects (MERP) = 9.00E+04 $ Field data
Reforest/soil cover = 5.00E+05 $ Field data
Total reclamation = 5.90E+05 $

Cost detail in Reforest/soil cover: $ 45000 in ZPR, $400000 ZPB and $ 55000 in ZP
Cost details in MERP: $ 22000 in ZPR,$ 22000 in ZPB, $ 23000 in Zp and $ 23000 in ZLP

20	TOP SOIL REMOVAL			
	Area removed (ZPR) =	90000	m^2	Field data
	Depth =	0.3	m	Field data
	Volume =	(90000 m2)(0.30m)		
	=	27000	m^3	
	Costs/unit =	20	$\$/m^3$	Field data
	Removal cost =	(27000 m3)(20\$)		
	=	5.40E+05	\$	

(defoliation for a period of 30 days), this zone was the largest (4500 ha). The next largest natural resource loss was agricultural production (row 14), equalling 4.6 E18 sej. Damage resulted in total loss of crops for 1/2 yr. Total natural resource losses were 17.5 E18 sej (5.3 E6 Em$).

The final group of losses are effects on the economic system (rows 15–20). Each of these items was evaluated in dollars. Row 15 is the dollar value of the spilled oil (at $21/barrel), which is evaluated separately from the energy value of the spilled oil in row 3. The largest single emergy flow was the value of the oil well that was destroyed (10.9 E18 sej). The clean up operation, totalling $1.38 million (7.1 E18 sej), was the second largest effect on the economic system. Row 18 is the money payments to farmers whose agricultural crops were lost. All affected farm land was in the lightly contaminated zone (ZLP) and suffered defoliation, but no permanent damage. In all, the total effects on the economic system were 31.0 E18 sej, or about 64% of the total losses (48.5 E18 sej).

It is important to note that the emergy value of the oil (item 3 in Table 1) is shown separately from natural resource losses and economic costs. The emergy value of the oil is a loss to the larger economy of Venezuela, but the spill results in a large input of organic matter to the spill region. With time, as the lighter, more toxic fractions of the crude oil are volatilized, the oil might be considered a concentrated input of organic matter, and thus it might be considered an input to the savannah.

Comparison between natural resource losses (17.5 E18 sej) and the emvalue of economic costs of restoration (31.0 E18 sej) are shown in Fig. 3. The emvalue of economic costs was almost twice the natural system losses. However, if the emergy

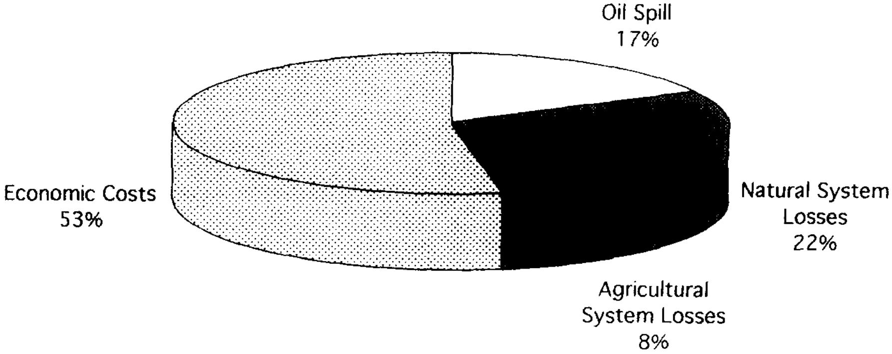


Fig. 3. Evaluation of the effects on the economy of clean up and restoration and natural resource impacts. All values are computed in Em$. Data are summarized in Table 1 (column 6).

value of the oil is considered an input of organic matter to the landscape, then emvalue of economic costs far exceeded natural system losses. If this is done then net natural resource losses total 7.6 E18 sej, roughly 25% of the emvalue of economic costs for clean up and restoration.

3.2. Natural resource impacts by zone

Impacts to natural resources are shown in Fig. 4a and b where estimated natural resource losses (biomass losses) for the 15 yr recovery time, are given by zone. The lightly polluted zone (ZLP) had the greatest biomass losses accompanied by some minor agricultural biomass losses. This zone was the only one that had agricultural uses. The zone that was polluted and burned had next highest total losses but were only about 20% of those in the ZLP. When biomass losses are depicted per unit area (Fig. 4b) the zone where soil was removed (ZPR) and the zone that burned (ZPB) had highest losses per unit area. The loss of productivity (GPP) over the 15-yr recovery time is shown in Fig. 5a and b. The highest total losses were in the ZLP and were concentrated in agricultural production (Fig. 5a), but when expressed as losses per unit area (Fig. 5b), the highest losses were in the ZPR, as a result of the longer recovery time.

Fig. 6 shows the estimated emergy value of natural resource losses and economic costs for the 15-yr recovery time, by zone. The zone of light pollution had largest estimated total losses, because of the larger area (4500 ha). On the other hand, when expressed as total losses on a unit area basis (Fig. 6b), the zone where polluted soil was removed was significantly higher than other zones. The greatest losses were the emergy costs of soil removal. Total unit area losses were over 60 E12 sej/m^2 and the economic costs of soil removal and replanting vegetation were over 66% of this total.

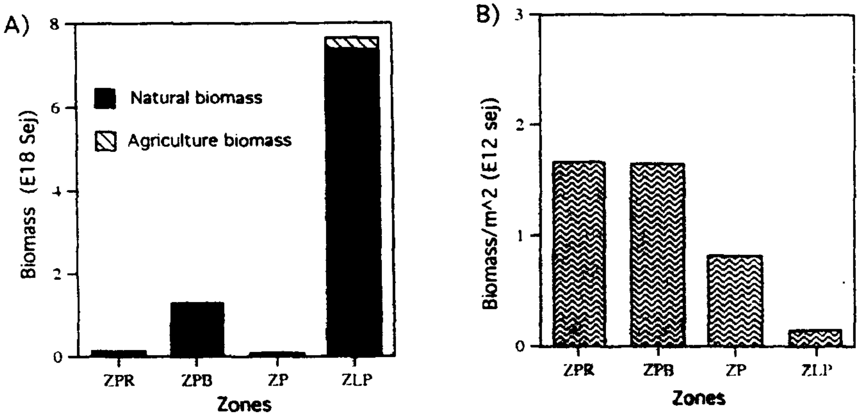


Fig. 4. Biomass losses by zones. All losses are given as sej. (a) Total biomass; (b) density of biomass losses. ZPR, zone affected by oil pollution and soil removal; ZPB, zone affected by oil pollution and burn; ZP, zone affected only by oil pollution and ZLP, zone lightly affected by oil pollution.

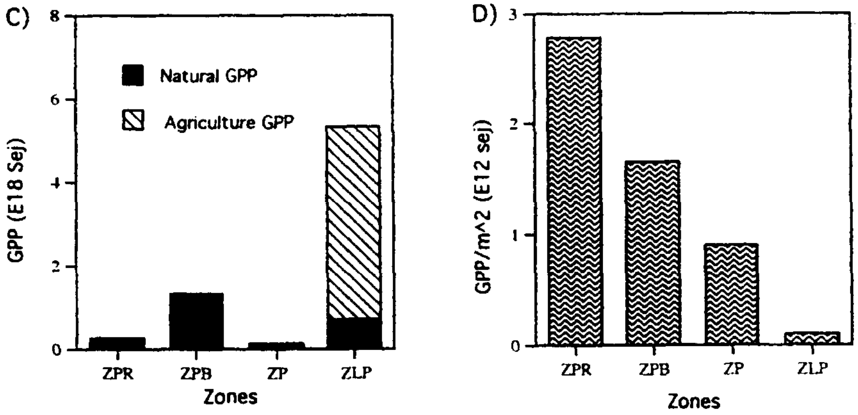


Fig. 5. Emergy equivalents of GPP losses by zones. All losses are given as sej. (a) Total GPP losses and (b) density of GPP losses. ZPR, zone affected by oil pollution and soil removal; ZPB, zone affected by oil pollution and burn; ZP, zone affected only by oil pollution; and ZLP, zone lightly affected by oil pollution.

Fig. 7 illustrates recovery of GPP (evaluated in emergy and expressed as sej/m^2 per yr) after the oil spill in each of the heavily oiled zones (ZP, ZPR, and ZPB) and the lightly oiled zone (ZLP). In Fig. 7a, the estimated total unit area losses (hatched area) in the ZPB (Fig. 7b) were almost twice those estimated in the ZP (Fig. 7c) while losses in the ZPR amounted to nearly three times those in the ZP. The smallest estimated unit area losses were in the ZLP (Fig. 7d).

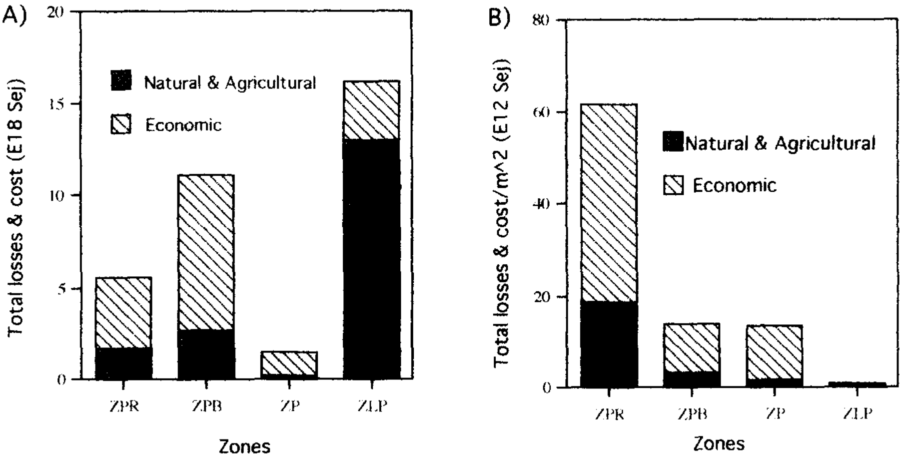


Fig. 6. Summary of natural resource damages and emvalue of economic effects, showing (a) total damages and emvalue of economic effects by zone and (b) damages and emvalue of economic effects per unit area. Loss of organic matter is included in natural resource damages. ZPR, zone affected by oil pollution and soil removal; ZPB, zone affected by oil pollution and burn; ZP, zone affected only by oil pollution and ZLP, zone lightly affected by oil pollution.

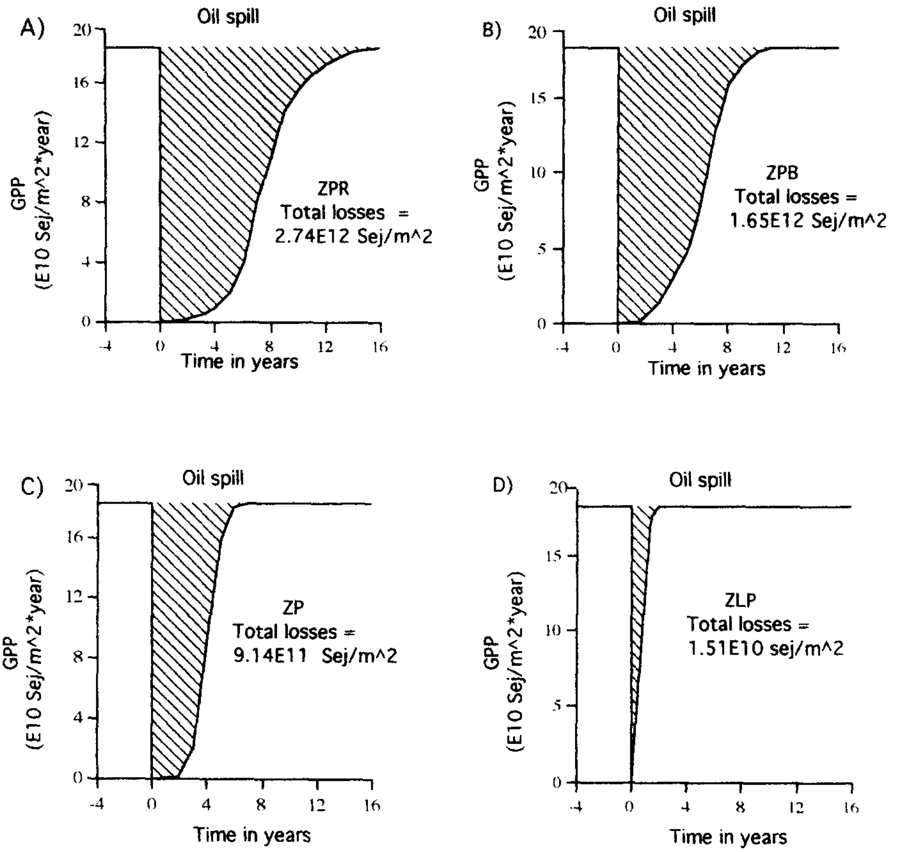


Fig. 7. Estimated losses of emergy equivalent of gross primary productivity (GPP) over time in (a) zone affected by oil pollution and soil removal (ZPR); (b) zone affected by oil pollution and burn (ZPB); (c) zone affected only by oil pollution (ZP); and (d) zone lightly affected by oil pollution (ZLP). Emergy equivalent of maximum GPP estimated as 1.8 E11 sej m^{-2} yr^{-1}.

It is apparent that the zone where soil was removed (ZPR) had greater unit area losses, primarily because of the longer time for recovery. The loss of top soil and all vegetative structure was estimated to take 15 yrs to replace, although this may not be sufficient time to replace total biodiversity, but only biomass and productive capacity. Field data collected on site (Prado et al., 1994b) and data from experimental growth plots (Prado et al., 1991, 1993) suggested that the area that was heavily oiled, but not burned or had its soil removed, would recover in a period of 5 yrs; nearly 1/3 the time for recovery compared to the zone where soil was removed. Clearly, soil removal was expensive (Fig. 6b) and in the end, may have had a deleterious effect on recovery. A better policy may have been to remove standing pooled oil with absorbent materials and allow natural recovery of vegetation as remaining oiled soil degraded.

Accidental burning of ZPB resulted in damage to standing vegetation in that zone. Because of oil saturation and coating of vegetation, the fire burned much hotter than normal fires in the savannah system, lengthening recovery time; estimated to require about 10 yrs. While the burning of ZPB was accidental, studies of recovery time suggest that the burned area will require twice the time to revegetate compared to the unburned zone. It appears that burning off residual oil may not be beneficial, and should be avoided, in favour of natural revegetation and some removal of pooled oil.

3.3. Costs and benefits of restoration

Clean up and restoration of the oil spill site provided the opportunity to evaluate the effectiveness of various cleanup strategies. Effectiveness might be determined relative to recovery without restoration activities. In other words, if natural restoration and recovery after an oil spill were to take 5 yrs, and as a result of restoration activities by humans it only takes 1 yr, then the effectiveness might be measured by the difference between the two recovery curves. Fig. 8 shows hypothetical curves for recovery after a disordering influence both with and without restoration activities. The difference between the two graphs (the hatched area between the two lines) is the 'benefit' of restoration. The energy, goods and services consumed in restoration activities are the costs. Thus we have the two terms necessary to calculate an emergy benefit/cost ratio. To be positive, the recovery time with restoration activities should be shorter than recovery time without restoration activities because total losses resulting from inhibition of GPP would be smaller.

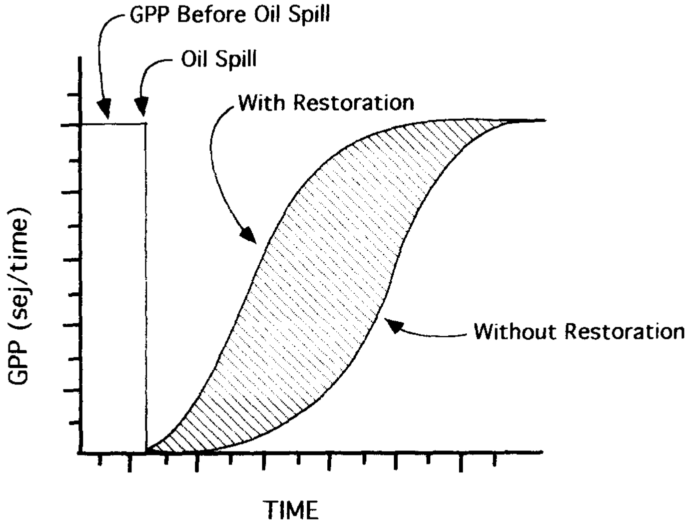
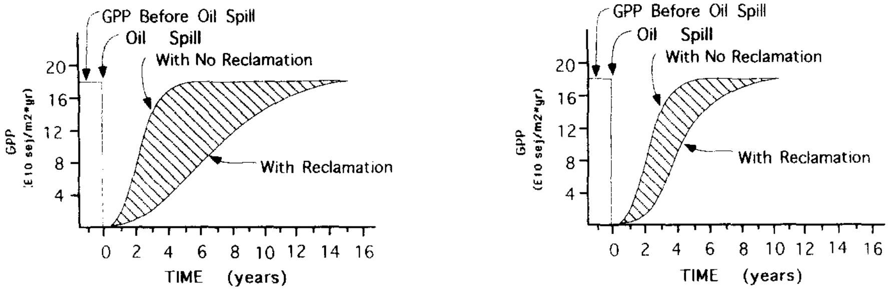
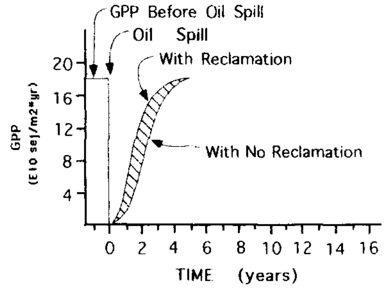


Fig. 8. Hypothetical curves of ecosystem recovery (measured by GPP) following a human induced disaster with and without restoration. The hatched area is the benefit of restoration.



a) Zone where soil was removed (ZPR)   b) Zone where oil was burned (ZPB)



c) Zone with only minor reclamation (ZP)

Fig. 9. Comparison of actual losses with estimated losses following reclamation activities in (a) ZPR; (b) ZPB; and (c) ZP. The shaded area is the difference between recovery with and without reclamation. In the case of the MUC-21 oil spill, the economic cost exceeded benefit in the zones of heaviest reclamation activities (ZPR) (see Fig. 1 for explanation of zones).

The graphs in Fig. 9 show estimated recovery of GPP for the ZPR (Fig. 9a), ZPB (Fig. 9b) and ZP (Fig. 9c). In the ZPR and ZPB, because of the negative impacts of soil removal and burning, the estimated recovery time was longer than it would have been without these treatments. The zone where soil was not removed (ZP) shown in Fig. 9c, yielded a positive benefit because recovery was faster than estimated recovery without reclamation activities. Yet, on average, $5000 U.S. per hectare were spent on reclamation activities in this zone, amounting to 2.55 E16 sej/ha. Since emergy equivalent of GPP in the savannah ecosystem prior to the spill was estimated to be 1.8 E15 sej/ha, to be effective, reclamation activities of this magnitude would have to speed up recovery by 28 yrs (assuming a straight line recovery). While recovery with these restoration activities (planting of grasses and soil conditioning) was faster than without restoration, it did not shorten recovery time with sufficient magnitude to yield a positive benefit/cost ratio. Certainly, the magnitude of activities that were undertaken did not yield sufficient benefits to warrant their undertaking.

3.4. Summary

From field data collected within the various zones it was clear that soil removal and oil burning will lengthen the time for ecological recovery, and result in negative benefits. Benefit/cost ratios for these zones would only yield negative ratios. The estimates of a 15-yr recovery time in the ZPR do not include the total ecosystem response to the oil spill, indeed, data on recovery of the animal community were not collected, thus this analysis accounts for only a portion of the total damages and recovery time. Benefit/cost ratios may be more negative than estimated here. Regardless, without the ability to express cleanup and restoration costs in the same units of measurement that increases in GPP are expressed, it is not likely that one could develop insight necessary to weigh these partial benefits against costs.

As a result of the analysis of recovery times it is quite clear that under some circumstances intensive efforts to remove oil may not be warranted. In a similar study of the Exxon Valdez oil spill (Brown et al., 1993) it was apparent that where restoration teams used high pressure steam to remove oil from the intertidal zone, more damage than good was done. Obviously, there is a point where restoration activities are no longer beneficial, but in fact, may cause more disorder that requires even greater flows of ordering energies and time to repair. Using emergy analysis the costs and benefits of restoration activities may be compared and decisions made regarding the most cost effective measures. In the larger context, restoration actions need yield positive benefits if they are to be valuable.

In areas where little or no restoration activities occurred, recovery was estimated to take from 1/3 to 1/15 the time required by areas where restoration was undertaken. The suggestion is the self-organization of nature, by engendering interface ecosystems, provides a better ecological engineering solution to oil spills, in this situation, than expensive technological efforts at restoration.

Acknowledgements

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Appendix A. Calculations of biomass and GPP transformities

Transformity of Savannah and Agricultural Biomass:

Transformities for biomass are based on total, supporting emergy flows. For savannah biomass, total emergy flow is the emergy of water transpired per year multiplied by the turnover time of the biomass assuming a steady state. For agriculture biomass, total emergy flow is sum of emergy in water transpired and purchased emergy.

Constants:
1.0 g organic matter = 3.6 kcal
1.0 kcal = 4186 J
Gibbs free energy rainwater = 4.94 J/g
Transformity of rain = 1.54 E4 sej/J (Odum, 1996)
Transformity of gd. water = 3.1 E4 sej/J (assume 2x rain)
Avg. transformity of ET assuming half from rain
and half from ground water sources = 2.57 E4 sej/J
Emergy/money ratio for Venezuela = 5.34 E12 Sej/$ (Appendix A)

Data:
Standing Biomass Savannah grasses = 0.85 kg/m^2 (Field data)
Standing biomass palm swamp = 3.9 kg/m^2 (Golley et al., 1988)
Turnover time Savannah grasses = 1-3 years (Field data)
(average of the following species: ***Paspalum notatum, Panicum maximun, Andropogon*** sp, ***Digitaria*** sp, ***Mimosa pudica, Shorgum helepense, Desmodium canum, Cypertus rotundus,*** *Cyperus odoratus, Rottboellia exaltata, Panicum faciculatum, Eleusine indica*
Turnover time of palm swamp = 30 years (Gonzalez-Boscan, 1990)
Mauritia flexuosa
Average agricultural biomass (corn and sorghum) = 0.70 kg/m^2 (Silva &Moreno, 1993)
Turnover time agricultural biomass (assuming a steady state) = 1 year (Silva &Moreno, 1993)
Average evapotranspiration, savannah = 1.44 m/yr (Sarmiento, 1984)
Evapotranspiration in corn and sorghum = 1.726 m (Casanova, 1991)

Calculations:

Average standing biomass for savannah is weighted average of grasses (50%) and palm swamp (50%).
Avg. biomass = 0.85 kg/m^2 * 0.50 + 3.90 kg/m^2 * 0.50 = 2.40 kg/m^2

Average turnover time for savannah is weighted average of grasses (50%) and palm swamp (50%).
Avg. turnover time = 2 yr * .50 + 30 yr * 0.50 = 15 years

Transformity of savannah biomass = ET (m/year) * (1000 kg/m^3) * Gibbs(J/kg) * Transformity (sej/J) * turnover time (year) / biomass (g/m^2) * 3.6 (kcal/g) * 4186 (J/kcal)

= 1.44 m/yea r* 1000 kg/m^3 * 4940 J/kg * 2.57E+4 sej/J * 15 year / 2,400 g/m^2 * 3.6 kcal/g * 4186 J/kcal
= 4.55E+04 sej/J

Transformity of agricultural biomass = Purchased flows (\$/m^{2}.year) * (Sej/\$) + Et (m/year) * (1000 kg/m^{3})*Gibbs(J/kg) * Transformity (sej/J) * turnover time (year) / biomass (g/m^{2}) * 3.6 (kcal/g)*4186 (J/kcal)
= 0.122 \$/m2*yr * 5.34 E12 sej/\$ +1.73 m/year * 1000 kg/m^{3} * 4940 J/kg * 2.571 E4 sej/J * 1 yr / 700 g/m^{2} * 3.6 kcal/g * 418 J/kcal
= 5.20E+04 sej/J

Transformity of Savannah Gross Primary Production and Agriculture Production:

Transformities for GPP are based on total, supporting emergy flows. For savannah GPP, total emergy flow is the emergy of water transpired per year. For agriculture production, total emergy flow is sum of emergy in water transpired and purchased emergy.

Data:

NPP palm swamp = 1.1kg/m^{2}*yr	(Myers, 1981)
NPP grassland = 300 g/m2*yr	(field data)
Sorghum and corn production = 510g/m2.year	(Casanova, 1991)
Purchased goods and services for corn and sorghum = 0.24 \$/kg = 0.1224 \$/m^{2}*year	(OCEI, 1991)

Calculations:

Average NPP for savannah is weighted average of grasses (50%) and palm swamp (50%).
Avg. NPP =1.1 kg/m^{2}*yr * 0.50 + 0.30 kg/m^{2} * 0.50 = 0.7 kg/m^{2}*yr
GPP assumed to be 5.3 * NPP = 5.3 * 0.7 kg/m^{2}*yr = 3.71 Kg/m^{2}*yr (Odum, 1978) (Brown and Arding, 1991)

Transformity of savannah GPP = ET (m/year)*1000kg/m^3*Gibbs No.(J/kg)*Trans. (sej/J)/ GPP (kg/m^2.year)*1000 (g/kg)*3.6 (kcal/g)*4186 (J/kcal)
= 1.44 m/year * 1000 * 4940 J/kg * 2.571 E4 sej/J / 3710 g/m^{2}.year * 3.6 kcal/g * 4186 J/kcal
= 2081 sej/J

Transformity of agriculture production = Purchased flows (\$/m^{2}.year) * (Sej/\$)+ET (m/year) * 1000(kg/m^{3}) * Gibbs No (J/kg) * RCPT(Sej/J)) /Production (g/m^2.year) * 3.6 (kcal/g) * 4186 (J/kcal)
= 0.122 \$/m2*yr * 5.34 E12(sej/J * 1.73 m/yr * 1000 kg/m^{3} * 4940 J/kg * 2.571 E4 sej/J / 500 g/m^2.year * 3.6 kcal/g * 4186 J/kcal
= 1.02 E5 sej/J

Appendix B. Calculation of emergy/money ratio for Venezuelan economy

Based on total emergy use in economy and Gross Domestic Product (GDP)

Total emergy use = sum of inflowing emergy (items: 3,6,7,8,15,18,19,20,21-32 in Table A-1 below)

GDP = 5.8E+10 $ (Source 2)

VENEZUELAN EMERGY/MONEY = Total Emergy Use/ GDP
= 3.01E+23sej/5.80E+10 $
=5.18E+12 sej/$

Table A-1 Emergy evaluation of resources basis for Venezuela (Period 1991 - 1992)

Note	Item	Amount	Units	Transformity* (sej/unit)	Solar Emergy (E18 sej/yr)	Emdollar (E6 U.S. Em$)
RENEWABLE RESOURCES:						
1	Sunlight	4.12E+21	J	1.00E+00	41.2	0.8
2	Rain chemical	6.74E+18	J	1.54E+04	1039.0	19.5
3	Rain geopotential	5.13E+18	J	8.89E+03	455.7	8.5
4	Wind	2.90E+18	J	6.23E+02	18.1	0.3
5	Waves	2.09E+17	J	2.59E+04	54.1	1.0
6	Tide	1.58E+17	J	2.36E+04	37.3	0.7
7	Earth cycle	2.00E+16	J	2.90E+04	5.8	0.1
8	River geopotencial	5.53E+18	J	8.89E+03	491.7	9.2
INDIGENOUS RENEWABLE ENERGY:						
9	Hydro-electricity	8.68E+16	J	1.59E+05	137.9	2.6
10	Agriculture prod.	1.78E+17	J	2.00E+05	355.1	6.7
11	Livestock prod.	1.04E+16	J	2.00E+06	207.0	3.9
12	Fisheries	1.47E+15	J	2.00E+06	29.5	0.6
13	Fuelwood prod.	5.15E+15	J	1.87E+04	1.0	0.0
14	Forest extraction	4.69E+15	J	3.49E+04	1.6	0.0
NONRENEWABLE SOURCES FROM WITHIN SYSTEM:						
15	Natural Gas	8.45E+17	J	4.80E+04	405.7	7.6
16	Oil	6.68E+17	J	5.30E+04	354.0	6.6
17	Thermoelectricity	1.10E+17	J	2.00E+05	220.3	4.1
18	fertilizers	3.93E+11	g	5.17E+09	20.3	0.4
19	Minerals	9.18E+12	g	9.20E+08	84.4	1.6
20	Top soil	5.27E+15	J	7.37E+04	3.9	0.1
IMPORTS AND OUTSIDE SOURCES:						
21	Oil derived prods.	4.95E+16	J	6.00E+04	32.7	0.6
22	Steel	8.80E+11	g	2.64E+09	23.2	0.4
23	Minerals	5.11E+12	g	9.20E+08	47.1	0.9
24	Ag & forest prod.	3.07E+16	J	2.00E+05	61.4	1.2
25	Livestock	1.12E+15	J	2.00E+06	22.3	0.4
26	Foods	8.12E+15	J	8.50E+04	6.9	0.1
27	Plastics & rubber	1.44E+16	J	6.60E+04	9.5	0.2
28	Chemicals	1.59E+12	g	3.80E+08	6.0	0.1
29	Wood,paper,textil	8.55E+15	J	1.30E+06	111.2	2.1
30	Mech. equip.	4.41E+11	g	6.70E+09	29.6	0.6
31	Service in imports	8.80E+09	$	2.00E+12	176.0	3.3
32	Tourism &paymnt	2.29E+09	$	2.00E+12	45.8	0.9
EXPORTS:						
33	Cash crops	1.91E+15	J	2.00E+05	3.8	0.1
34	Fishery products	1.29E+15	J	2.00E+06	25.8	0.5
35	Livestock	1.95E+14	J	2.00E+06	3.9	0.1
36	Oil & derives.	4.14E+18	J	6.00E+04	2481.5	46.5

37	Steel	1.80E+13	g	2.64E+09	475.2	8.9
38	Minerals	7.10E+12	g	9.20E+08	65.4	1.2
39	Chemicals	8.39E+11	g	3.80E+08	3.2	0.1
40	Service in exports	4.35E+08	$	5.18E+12	22.5	0.4
41	Tourist service	2.00E+08	$	5.18E+12	10.4	0.2

* All transformities are from Odum, 1996, except Venezuelan Emergy/$ ratio which was calculated from this data.

Footnotes to Table 1

RENEWABLE RESOURCES:

1 SOLAR ENERGY
Continental shelf = 8.81E+10 m^2 at 200 m depth Source 20
Land area = 9.16E+11 m^2 Source 14
Insolation = 1.40E+02 Kcal/m^2/yr Source 1
Albedo = 0.30 (% given as decimal) Source 13
Energy = (Area)(Avg. insolation)(1-albedo)*4186J/kcal
(1.0E+12m^2)(140Kcal/cm^2/year)(1.0E+04cm^2/m^2)* (1-0.30)*4186J/kcal
Energy = 4.12E+21 J/yr

2 RAIN CHEMICAL POTENTIAL ENERGY
Land Area = 9.16E+11 m^2 Source 14
Cont. Shelf Area = 8.81E+10 m^2 at 200 m depth Source 20
Rain (land) = 1.44 m/yr Source 1,18
Rain (shelf) = 0.50 m/yr Estimate
Energy land = (Area of land)(Evapotrans)(Chem.Pot Energy/kg)
= (9.16E+12m^2)(1.44m/yr)(1000kg/m^3)(4.940J/kg)
= 6.52E+18 J
Energy shelf = (Area of shelf)(Rainfall)(Chem.Pot Energy/kg)
= (8.81E+10m^2)(0.5m)(1000kg/m^2)(4940J/kg)
= 2.18E+17 J/yr
Total energy = Energy land plus energy shelf
= 6.74E+18 J/yr

3 RAIN GEOPOTENTIAL ENERGY
Area = 9.16E+11 m^2 Source 14
Rainfall = 2.03 m Source 1
Elevation average = 375.00 m Average of 30 city Source 8
Runoff rate = 0.75 River flow/Rain*Land Source 21, 1, 5, 23
Energy = (Area)(% Runoff)(Rainfall)(Avg. elevation)(Gravity constant)
Energy = (9.16E+11m^2)(2.03m)(1000kg/m^3)(375m)(9.8m/s^2)0.75
Energy (J) = 5.13E+18 J/yr

4 WIND ENERGY
Avg. wind range = 2.7 m/s Source 1
Energy = (Area)(Atm. layer)(Air dens.)(Air specific heat)(Horiz. temp. grad.)(Wind)
Energy = (9.16 E+11m^2)(1000m)(1.23kg/m^3)(0.24 kcal/°K)(2.7m/s) (3.0E-09°/m)*4186J/kcal* 3.154 E+7s/year
Energy (J) = 2.90E+18 J/yr

5 WAVE ENERGY
Wave height = 1.2 m and Wave depth = 0.7 m Experimental data from 5 port
Length coast exposed = 1.40E+06 m Measured from map Source 14
Depth factor = 1/8*Wave heigth^2*(Gravit. const.*wive depth)^1/2
Energy = (Sea water density)(Length coast exposed)(Gravit. constant)(Depth factor)
Energy = 1/8*1025kg/m^3*1.4 E+6m*9.8m/s^2*[1.2m]^2*[9.8 m/s^2*0.7m]$^{1/2}$* 3.154 E+7 s/yr
= 2.09E+17 J/yr

6 TIDAL ENERGY
Cont. shelf area = 8.81E+10 m^2 Source 20
Average tide range = 0.70 m Source 14
Density = 1.03E+03 kg/m^3 Source 13
Tides/year = 7.30E+02 (Estm. of 2 tides/day in 365 days)

Energy = (Shelf)(0.5)(tides/y)(mean tidal range)^2 (density of seawater)(gravity)
Energy = (8.81E+10 m^2)*0.5*730tides/yr*(0.7m/tide)^2*1025kg/m^3* 9.8m/s^2
= 1.58E+17 J/yr

7 EARTH CYCLE
Area = 3.20E+16 cm^2 Mountain area (measured) Source 14
Uplift = 1.25E-02 cm/yr Estimate
Density = 2.60 g/cm^3
Energy = (Area)(Uplift)(Density)(Gravit. constant)
(conversions)*0.5
Energy = 2.00E+16 J/yr

8 RIVER GEOPOTENTIAL
Flow of Venezuela = 3.00E+04 m^3/s Source 21 &10
Flow frm Colombia = 1.40E+04 m^3/s Source 21
Average Elevation = 3.75E+02 m Source 8
Average Elev. Col. = 4.75E+02 m Source 3
Energy = [(Ven. flow)(Ven. elev.)+(Col flow)(Col elev.)] *9.8m/s^2* 3.154E+07s/yr *1000kg/m^3
Energy = [(3.0E+04m^3/s)(375m)+(1.4E+04m^3/s)(475m)] *9.8m/s^2* 3.154E+07s/yr *1000kg/m ^{3}
Energy = 5.53E+18 J/yr

INDIGENOUS RENEWABLE ENERGY

9 HYDROELECTRICITY
Kilowatt Hrs/year = 2.41E+10 KwH/year Source 5 & 20
Energy = (KwH/yr)(3.60E+06J/KwH)
Energy = 8.68E+16 J/yr

10 AGRICULTURAL PRODUCTION
Agricultural Prod. = 1.21E+07 MT/year Source 20 & 7
1.0 g biomass = 3.5 to 3.6 Kcal/g Source 4
Energy = (1.21E+07MT/yr)(1E+6g/MT)(3.6Kcal/g)(4186J/Kcal)
Energy = 1.78E+17 J/yr

11 LIVESTOCK PRODUCTION
Livestock Prod. = 2.81E+06 MT/year Source 20 & 7
Energy = (2.81E+6 MT/yr)(1E+6 g/MT)(4 kcal/g)(4186 J/kcal)*
0.22 (this number represents 22% protein)
Energy = 1.04E+16 J/yr

12 FISHERIES PRODUCTION
Fish catch = 4.00E+05 MT/yr Source 7
Energy = (4.0E+5MT/yr)(1E+6g/MT)(4 kcal/g)(4186J/kcal)*
0.22 (22% protein)
Energy = 1.47E+15 J/yr

13 FUELWOOD PRODUCTION
Fuelwood Prod = 6.84E+05 m^3 Source 20
Wood density = 5.00E+05 g/m^3 Source 4
Energy = (6.84E+05 m^3)(5E+05 g/m^3)(3.6 kcal/g)(4186 J/kcal)
Energy = 5.15E+15 J/yr

14	FOREST EXTRACTION			
	Harvest =	6.23E+05	m^3	Source 20
	Energy =	(6.32E+6 m^3)(5E+5 g/m^3)(3.6 kcal/g)(4186 J/kcal)		
	Energy =	4.69E+15	J/yr	

NONRENEWABLE RESOURCE USE FROM WITHIN VENEZUELA

15	NATURAL GAS			
	Given:	1 ft^3=1031 BTU		Source 4
	Consumption =	7.77E+11	ft^3/yr	Source 7
		1 BTU = 1055 Joules		Source 6
	Energy =	(7.77 E+11 ft^3/year)* 1031 BTU/ft^3*1055 J/BTU		
	Energy =	8.45E+17	J/yr	
16	OIL			
	Consumption =	3.00E+05	barrels/day	Source 16
	Energy =	(2.5E+05barrels/day)(365days/y)*6.1E+09Joules/barrel		
	Energy =	6.68E+17	J/yr	
17	THERMOELECTRICITY			
	Consumption =	3.06E+10	KwH/yr	Source 20
	Energy =	(3.06E+10KwH/year)(3.6E+06J/KwH)		
	Energy =	1.10E+17	J/yr	
18	FERTILIZER (Grams per year)			
	Consumption =	3.93E+05	MT/yr	Source 20
	Energy =	(3.93E+05MT/year)(1E+06g/MT)		
	Energy =	3.93E+11	g/yr	
19	MINERALS (Grams per year)			
	"(Au, Ag, Pb, Cu, Zn, Coal, Coke, Iron, Mn, sulphur)"			
	Consumption =	9.18E+06	MT/yr	Source 7
	Energy =	(9.18+E06MT)*1E+06g/MT		
	Energy =	9.18E+12	g/yr	
20	TOPSOIL LOSS:			
	Soil loss =	8.50E+02	g/m^2.yr	Source 11
	Arable zone =	2.75E+09	m^2	Source 5
	Soil loss = Arable zone*SFL			Source 4
		(2.75E+9m^2)*(8.5E+02 g/m^2.yr)		
	Soil loss =	2.33E+12	g/yr	
	Average % OM	1.00	%	Source 18 & 17
		1 g of O.M. is 5.4Kcal		Source 4
	Energy =	(2.33E+12g/yr)(0.01organic)(5.4Kcal/g)(4186J/Kcal)		
	Energy =	5.27E+15	J/yr	

IMPORTS OF OUTSIDE ENERGY SOURCES:

21	OIL DERIVED PRODUCTS			
	Import =	1.21E+09	l/yr	Source 11
	Energy =	(1.21E+9l/yr)(41E+06J/l)		
	Energy =	4.95E+16	J/yr	
22	STEEL (Grams per year)			
	Imports =	8.80E+05	MT/yr	Source 11
	Energy =	(8.80E+05 MT/yr)(1E+06g/MT)		
	Energy =	8.80E+11	g/yr	

23 MINERALS (Grams per year)
"Metal, non-metal,Al, Cu & Ni"
Imports = 5.11E+06 MT/yr Source 11
Energy = (5.11E6MT/yr)(1E+06g/MT)
Energy = 5.11E+12 g/yr

24 AGRIC. & FOREST. PRODS
Imports = 2.10E+06 MT/yr Source 11
Energy = (2.10E+6MT/yr)(1E+06g/MT)(3.6 Kcal/g)*4186J/Kcal
Energy = 3.07E+16 J/yr

25 LIVESTOCK
Imports = 3.03E+05 MT/yr Source 11
Energy = 3.03E+05MT/yr)(1E+06g/MT)(4Kcal/g)*4186J/Kcal* 0.22 (22%proteins)
Energy = 1.12E+15 J/year

26 FOODS
Imports = 5.37E+05 MT/yr Source 11
1.0 g food = 15100 Joules/g Source 4
Energy = (5.37E+5 MT/yr)(1E+06g/MT)15.1E+03 J/g
Energy = 8.12E+15 J/yr

27 PLASTICS & RUBBER
Imports = 1.53E+06 MT/yr Source 11
1.0 g Chem. products = 9.4E+06Joules/kg Source 4
Energy = (1.53E+05MT/yr)(1000Kg/MT)*9.4E+06J/kg
Energy = 1.44E+16 J/yr

28 CHEMICALS (Grams by year)
Imports = 1.59E+06 MT/yr Source 11
Energy = (1.59E+06MT/yr)*1.0E+06g/MT
Energy = 1.59E+12 g/yr

29 WOOD, PAPER, TEXTILES, LEATHER
Imports = 5.70E+05 MT/yr Source 11
1.0 g food = 15100 Joules/g
Energy = (5.70E+05MT/yr)(1E+06g/MT)*15.1E+03J/g
Energy = 8.55E+15 J/yr

30 MACHINERY, TRANSPORTATION EQUIPMENT (grams by year)
Imports = 4.41E+05 MT/yr Source 11
Energy 4.41E+05MT/year)*1.0E+06g/MT
Energy = 4.41E+11 g/yr

31 SERVICES (Dollar by year)
Dollar value = 8.80E+09 $US Source 11

32 TOURISM & OTHERS (Dollars by year)
Dollar value 2.29E+09 $US Source 11
Dollars paid for imports = 1.20E+10 $US Source 5

EXPORTS OF ENERGY

33 CASH CROPS
Agriculture & Forestry = Coffee, tomatoes, vegetables, fresh fruits, cacao, others
Exports = 1.31E+05 MT/yr Source 1
Energy = (1.31E+05MT/yr)(1E+06g/MT)*3.5kcal/g* 4186 J/kcal
Energy = 1.91E+15 J/yr

34 FISHERY PRODUCTION
Exports = 3.50E+05 MT/yr Source 7
Energy = (3.50E+05MT/yr)(1E+06g/MT)(4 kcal/g)*4187J/kcal* 0.22 (22% proteins)
Energy = 1.29E+15 J/yr

35 LIVESTOCK
Exports = 5.30E+04 MT/yr Source 11
Energy = (5.30E+04MT/yr)(1E+06g/MT)(4Kcal/g)*4186J/kcal* 0.22(22% proteins)
Energy = 1.95E+14 J/yr

36 DERIVED OIL
Exports = 6.78E+08 Barrels/yr Source 11, 9, & 15
Energy = (6.78E+08Barrels/yr)*6.1E+09J/Barrel
Energy = 4.14E+18 J/yr

37 STEEL & METALLIC PRODUCTS (Grams by year)
Exports = 1.80E+07 MT Source 20
Energy = (1.8E+07MT/yr)*1E+06g/MT
Energy = 1.80E+13 g/yr

38 MINERALS (Grams by year)
"Metal, non-metal, Al, Coal, Bauxite, Etc."
Exports = 7.10E+06 MT/yr Source 11, 5 & 7
Energy = (7.10E+06MT/yr)*1E+06g/MT
Energy = 7.10E+12 g/yr

39 CHEMICALS (Grams by year)
Exports = 8.39E+05 MT/yr Source 11
Energy = (8.39E+06MT/yr)*1E+06g/MT
Energy = 8.39E+11 g/yr

40 SERVICES IN EXPORTS:
Dollar Value = 4.35E+08 $US Source 5

41 TOURISM SERVICES:
Dollar Value = 2.00E+08 $US Source 7

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