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ENERGY ANALYSIS, RICE PRODUCTION SYSTEMS, AND RICE RESEARCH

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ABSTRACT

It has become fashionable to calculate energy efficiency ratios of agricultural production systems, including rice. A question raised is whether IRRI should explicitly consider this criterion when establishing its research priorities.

We argue that using energy efficiency as a normative choice criterion has theoretical and empirical shortcomings. The approach may not result in research priority selection which leads to technology relevant to farmers or grain types acceptable to consumers. Price weights are preferable to energy weights to reflect input scarcity and market preferences. Economic evaluation, supported by equity analysis, seems to remain the appropriate guide for IRRI when determining research priorities and evaluating the relevance of its research output.

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ENERGY ANALYSIS, RICE PRODUCTION SYSTEMS, AND RICE RESEARCH

During the last two decades, agricultural development has increasingly relied on a combination of new varieties and additional support energies (mainly fertilizer, pesticides, fuels, and irrigation) to increase agricultural productivity. This reliance on energy has been coupled with an increasing demand for food from population increases and increased affluence. The public has become increasingly aware that supplies of fossil fuels are limited, and this led to worldwide concern about both energy and food in the early seventies. This concern was highlighted by the *oil-embargo* in 1972-73 when energy, fertilizer, and food prices rose rapidly in domestic and international markets.

Two concerns were uppermost. First, could energy-importing countries meet higher energy bills and sustain economic growth? Second, at the current rates of use, what would be the future availability of finite stocks of energy, especially fossil fuels? Energy analysis and energy efficiency, therefore, became increasingly important yardsticks in formulating energy policies (23).

The early focus of research in energy analysis (EA) was to inventory energy requirements and energy efficiencies in developed countries (eg, 16). These analyses demonstrated that modern food production systems were less energy efficient than more traditional forms (Fig. 1). Geographers, in particular, argued for the return of western agriculture to more energy-efficient methods. However, they rarely considered whether these systems had the productive capacity to sustain current or future populations.

Proponents of energy efficiency usually compare alternative food production systems in terms of their energy ratio (ER). The ER of a process is:

$$ER = O_i / I_i \qquad (1)$$

where

O_i is the output energy (gross, digestible or metabolizable) of crop i, and

I_i is the energy input, other than solar energy, to produce O_i.

This method implies that energy can be aggregated regardless of source, form, scarcity, or productivity. That is:

$$O_i = \sum_{j=1}^{n} E_j Y_j \quad \text{and} \quad I_i = \sum_{k=1}^{m} E_k X_k \qquad (2)$$

where

E_j is the unit energy content of component Y_j of biomass output, and

E_k is the unit energy of input X_k necessary to produce Y_j.

Labor has unusual characteristics — it provides both energy and management. Therefore, the denominator of equation 1 may be respecified as

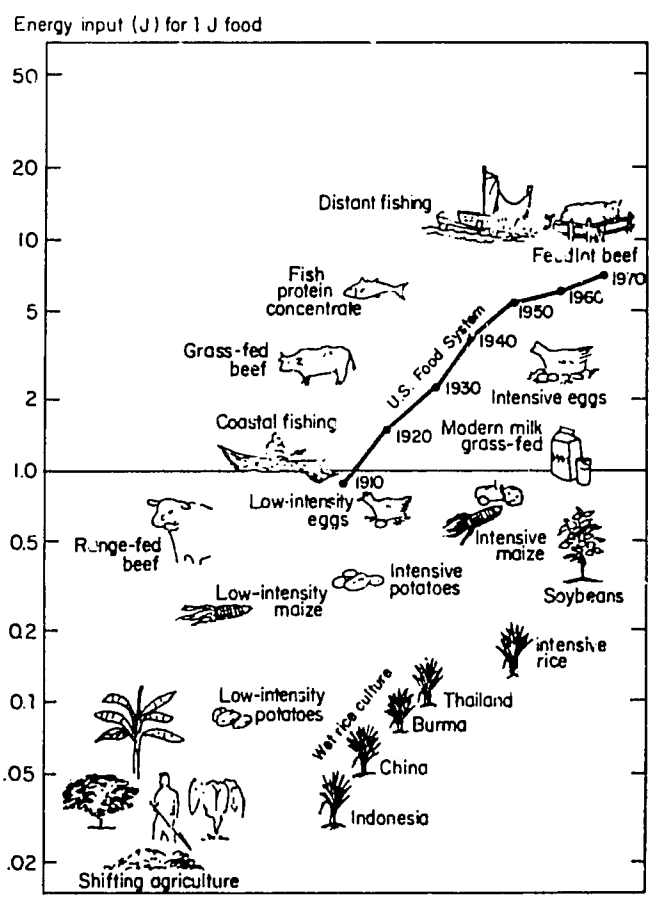
$$E_e + L_I \qquad (3)$$

where

E_e is the energy content of nonlabor and L_I is the energy content of labor inputs.

RICE ENERGY BUDGETS

We assembled a series of energy budgets to represent a range of rice production systems. The input-output data underlying the analysis are presented in Table 1 and provide a breakdown of energy use by input components including human labor, animal power, seed, fertilizer, pest control chemicals, mechanization, and irrigation. The data source for each system is noted in Table 1; reliability and completeness vary widely. This highlights one of the critical problems



1. Estimated energy inputs for various food-producing systems (20).

Table 1. Indicative values/input components of rice production systems (per hectare basis).

Description	Source	Human labor (h)	Animal labor (h)	Seed (kg)	Fertilizer (kg N equivalent)	Insect herbicide (kg ai)	Machine (kg)	Machine fuel (litre)	Irrigation	Yiel (t/h
1. Upland Latin America	(22)	450		50						1.20
2. Rainfed unfavorable	(12)	352	84	80	15	0.50	4			1.50
3. Rainfed unfavorable	(CP)	540	112	72	20	1.00	4			1.80
4. Rainfed unfavorable	(12)	656	120	60	15	0.50	4			2.10
5. Rainfed favorable	(12)	448	120	80	19	0.50	4			2.20
6. Rainfed favorable	(12)	860	168	60	19	0.50	4			2.60
7. Irrigated Japan	(21)	870		40	40	0.70	50	203	120	4.55
8. Irrigated Laguna	(18)	763		60	88	0.70	10	50	100	4.10
9. Irrigated Rice Garden	(13)	580		60	110	3.40	7	26	100	4.00
10. Irrigated organic Chinese	(24)	5085		60	127		7		120	9.60
11. Irrigated Azolla	(9)	588	60	60	30	1.50	5	12	100	4.60
12. Deep water	(4)	800	286	83			4			2.7
13. Upland broadcast	(25)	922	39	60	68		4			1.90
14. Irrigated Philippine dry season (DS)	(CS)	560	30	50	121	0.70	7	25	100	4.70
15. Irrigated Philippine DS	(CS)	640	30	50	121	4.20	7	25	100	5.60
16. Irrigated Philippine DS	(CS)	640	30	50	190	0.70	7	25	100	5.70
17. Irrigated Philippine DS	(CS)	640	30	50	190	4.20	7	25	100	6.20
18. Irrigated Philippine DS	(CS)	560	30	50	130	2.00	7	25	100	5.00
19. Irrigated Philippine DS	(CS)	640	30	50	130	5.50	7	25	100	5.90
20. Irrigated Philippine DS	(CS)	640	30	50	190	2.00	7	25	100	6.00
21. Irrigated Philippine DS	(CS)	640	30	50	190	5.50	7	25	100	6.80

Index from Pimentel (16). CS = Consequences Study, 1975-77, CP = Consequences Project, 1981.

Table 2. Energy components of alternative rice production systems (in MJ).

Description	Human labor	Animal labor	Seeds	Fertilizer (kg N)	Insect herbicide	Machine	Machine fuel	Irrigation	Yield (unmilled rice)
1. Upland Latin America	471		617						14820
2. Rainfed unfavorable	368	647	987	1216	54	368			18520
3. Rainfed unfavorable	565	863	889	1621	107	368			22230
4. Rainfed unfavorable	686	925	740	1216	54	368			25930
5. Rainfed favorable	469	925	987	1540	54	368			27170
6. Rainfed favorable	900	1295	740	1540	54	368			32110
7. Irrigated Japan	910		494	3242	75	4603	5750	5523	56190
8. Irrigated Laguna	798		740	7152	75	920	1416	4602	50630
9. Irrigated Rice Garden	607		740	8915	364	644	736	4602	49400
10. Irrigated organic Chinese	5319		740	8915	364	644	736	4602	49400
11. Irrigated Azolla	615	462	740	2431	160	460	340	4602	56810
12. Deep water low input	837	2204	1024			368			33350
13. Upland broadcast	964	300	740	5511		368			23470
14. Irrigated Philippine dry season (DS)	586	231	617	9807	75	644	708	4602	58040
15. Irrigated Philippine DS	669	231	617	9807	449	644	708	4602	69160
16. Irrigated Philippine DS	669	231	617	15399	75	644	708	4602	70390
17. Irrigated Philippine DS	669	231	617	15399	449	640	708	4602	76570
18. Irrigated Philippine DS	669	231	617	10536	214	644	708	4602	61750
19. Irrigated Philippine DS	669	231	617	10536	588	644	708	4602	72870
20. Irrigated Philippine DS	669	231	617	15399	214	644	703	4602	74100
21. Irrigated Philippine DS	669	231	617	15399	588	644	703	4602	93980

of energy analysis — the availability of comprehensive, comparable input/output data to allow unbiased comparisons between systems.

The input-output data were transformed into energy equivalents (Table 2) using the conversion factors listed in Appendices 1 and 2. The energy ratio calculated for each system is summarized in Table 3. Although the absolute levels of energy and the efficiency ratios may be challenged, the relative rankings are reasonable.

ENERGY RATIOS AND PRODUCTIVITY

The ER's of wetland rice typically fall in the range of 3-9. Thus, unlike many industrial processes, there is a significant net output of energy, even in the least *energy-efficient* rice production systems. However, the ratios per se do not provide insights into the energy output (E_o) or human support capacity of individual agricultural systems. Thus, the relationship between ER and output of each rice

Table 3. Total energy embodied in inputs and yield for alternative rice production systems.

Description	Energy (MJ)		
	Inputs	Output[a] (brown rice)	ER
1. Upland Latin America	1087	18995	17.46
2. Rainfed unfavorable	3640	23748	6.52
3. Rainfed favorable	4416	28497	6.45
4. Rainfed unfavorable	3991	33246	8.33
5. Rainfed favorable	4343	34828	8.02
6. Rainfed favorable	4899	41163	8.40
7. Irrigated Japan	72682	72037	3.18
8. Irrigated Laguna	16179	64912	4.01
9. Irrigated Rice Garden	16866	63330	3.75
10. Irrigated organic Chinese	22405	118560	5.29
11. Irrigated Azolla	9933	72828	7.33
12. Deep water low input	4528	33345	7.36
13. Upland broadcast	7882	30079	3.82
14. Irrigated Philippine dry season (DS)	17518	74410	4.25
15. Irrigated Philippine DS	17974	88661	4.93
16. Irrigated Philippine DS	21392	90242	3.89
17. Irrigated Philippine DS	23592	98158	4.16
18. Irrigated Philippine DS	18384	79163	4.31
19. Irrigated Philippine DS	18845	93325	4.96
20. Irrigated Philippine DS	23330	94995	4.07
21. Irrigated Philippine DS	23707	107661	4.54

[a]Brown rice specified as 78% by weight the yield of paddy rice.

production system described in Table 1 is graphed in Figure 2. In general, energy output and energy ratios are inversely related. For example, the most energy-efficient system examined was one of upland rice in Latin America (22). However, because it produces 1.2 t/ha per crop, its support capacity is low — probably less than 4 persons/ha per year. Dry season (irrigated) rice in the Philippines (10) has an energy ratio of less than 5.0 but has a high support capacity of nearly 7 t/ha of rough rice.

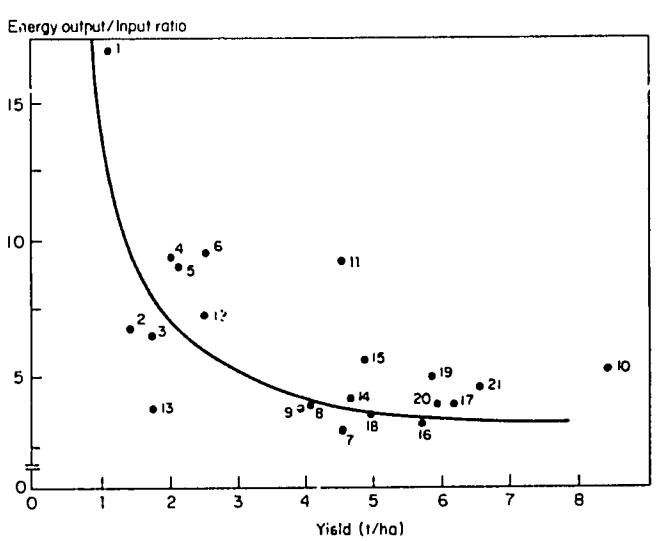
Sites 10 (China) and 11 (Azolla) deserve special mention. The Chinese claim nearly 10 t/ha per crop of rough rice; the large energy inputs are labor and organic fertilizer. Although energy inputs are high in the Chinese example, output is sufficiently large to generate a favorable ER. The azolla case is unique in that N is supplied organically at low energy cost. The levels of azolla productivity in Southern Cotabato (attributed to high P levels in irrigation water) are not generally found in the tropics and the widespread use of azolla has yet to be assessed.

The challenge is to increase the ER of rice systems without reducing support capacity. Basically, the problem is to shift the ER curve in Figure 2 upward and to the right. Specifically, for a given rice environment, how can ER be increased without materially reducing productivity? A fundamental principle of crop biology is that as inputs (E_i) increase, output (O_i) likewise increases but at a decreasing rate, when technology remains constant (Fig. 3). Therefore, the energy ratio, $ER = O_i/I_i$ (ie, tan θ), diminishes as I_i increases.

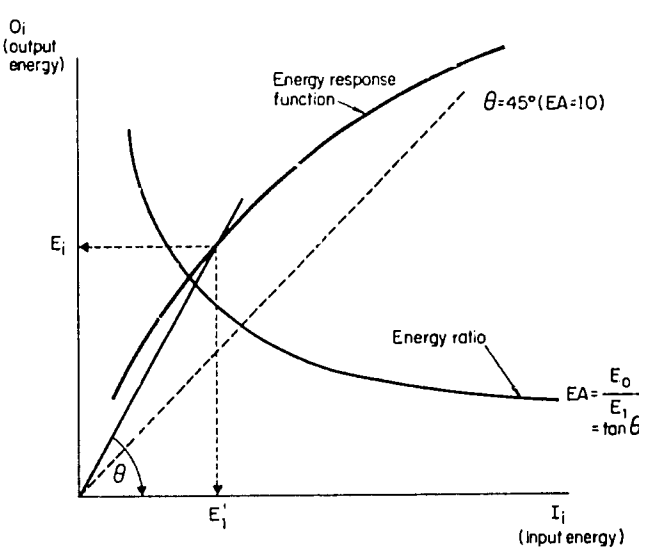
Thus, the research challenge is to increase output without sliding down the energy efficiency curve. That is, how can the energy response function (Fig. 3) be moved upward and to the left? A short-term solution is to increase technical efficiency by applying current technology. IRRI's constraints analysis shows that such gains may be moderate on average, possibly in the order of 5-10% (5, 8). This conforms to the notion that most low-resource farmers, given the circumstances they face, are tolerably efficient from a technical viewpoint.

On this basis the research objective may be to generate technology which is more energy efficient than farmers now have access to. Increased energy efficiency in rice culture may result from a combination of

1. increased efficiency in manufacturing and marketing of agricultural inputs such as agrochemicals and machines,
2. increased on-farm efficiency in inputs use, and
3. increased efficiency in the use of the rice plant biomass.



2. Yield and energy efficiency for alternative rice production systems. (Numbers refer to production systems in Table 1.)



3. Crop-energy response relationship and energy ratio (EA), assumin technology is fixed.

Energy use in urea production, for example, may be reduced as much as 30% from a present 80 GJ/t to a future 54 GJ/t as new fertilizer plants are built using current technology (14). Much of this energy saving would come from increased operating efficiency by improved use of capacity, particularly by avoiding frequent shutdown of ammonia-urea plants.

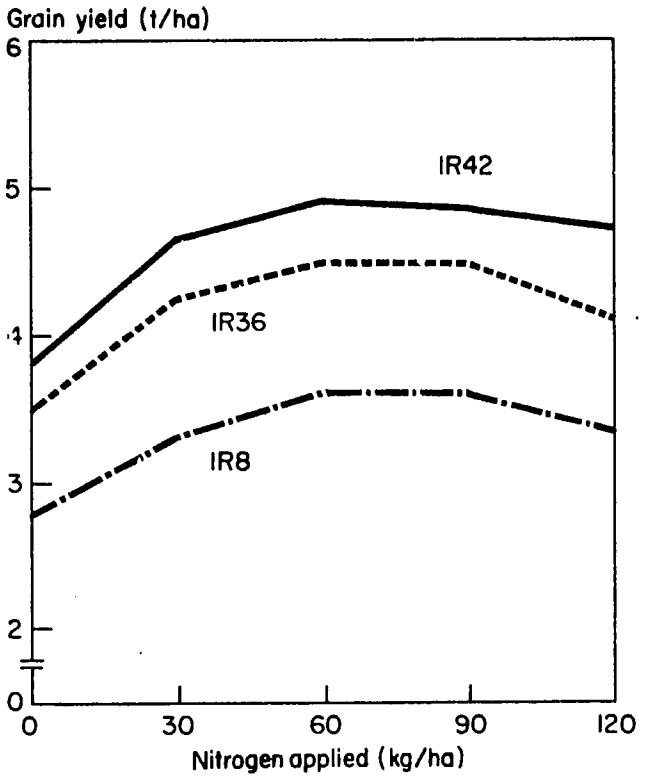
RICE RESEARCH TO INCREASE ENERGY EFFICIENCY

IRRI's research advantage lies in efficiency elements 2 and 3. A nonexhaustive list of Institute activities which should contribute to increased energy efficiency in rice production appears in Table 4. Varietal improvement is a key to increased energy efficiency. First, the technology embedded in a rice seed comes to the farmer at basically no added cost; it is resource and scale neutral in application, and for practical purposes does not depend on management for success. Second, varieties or genetic traits tend to be less location-specific than crop management methods. seed technology tends to apply over broad areas wit aggregate benefits. Third, there is no trade-off b economic and energy efficiency, providing there is no trade-off between yield and energy-related objectives

This paper does not attempt an *ex-ante* assessm IRRI research from an energy viewpoint. However, discussion of selected cases is in order. Breeders w produce cultivars which increase yield stability and reliance on costly inputs, many of which are intensive. Thus, new varieties are more energy efficien first-generation modern varieties such as IR8 and IR example, IR42 is significantly more N-efficient than earlier cultivars (Fig. 4) and tolerates Zn and P nu deficiencies. Similarly, the second- and third-gene modern varieties have improved insect and disease ance (Table 5), reducing the need for energy-expe chemical protection.

Table 4. Examples of IRRI research which should contribute to increases in energy efficiency in rice production.

Research area	Example	Possible impact
I. *Varietal improvement*		
Plant breeding/GEU	Increasing solar energy efficiency	Increased wet season yield potential to 8.2 t/h dry season yields to 12.5 t/ha.
	Efficiency in use of soil nutrients	Higher yields for same levels of applied nutrient reduced application of micronutrients such as z
	Effective use of soil moisture	Increased yield and yield stability in rainfed environments
	Tolerance for biological and physical stresses	Reduced use of insecticides and fungicides. Cro adaptation to adverse environments.
	Increasing harvest index	Higher conversion of total energy input to commercial output – grain.
II. *Increased efficiency of input use*		
Nutrient management	N formulations/placement	Increased (30-60%) N efficiency
	Azolla	Up to 100 kg N fixed/crop
	Straw incorporation	Increased (up to 0.4 t/ha) yields
Pest management	Integrated management	Reduced insecticide sprays (from current 4-6 d to 1-2).
	Neem oil	Natural (flow) energy source for pest managem
Water management	Irrigation system management	10-60% increase in rice output for same water delivery to system.
	Axial-flow pumps	Increased energy efficiency for low lifts (33% than centrifugal pumps)
Tillage	Minimum tillage	Reduced energy and water inputs in land prepara
III. *Increased use of rice biomass*		
Crop improvement	Increasing harvest index	Higher conversion of total energy input to commercial output – grain
	Higher straw palatability	Increased value of rice straw as livestock feed.
Postharvest	Threshing	Reduced (6-10%) threshing losses
	Vortex drier	Use of local fuel and wind vortex, reduced losses, and increased quality of rice grain.
	Milling	4-6% increase in head rice recovery.
Nongrain biomass	IRRI/UPLB/ADB *Prosperity through rice farming systems*	Alternative opportunities for utilizing straw (eg, paper making, feed mushroom culture, biogas), h (fuel, silicon for photovoltaic cells), bran for livestock feed, oil extraction.



4. Grain yield response of IR8, IR36, and IR42 to 4 levels of nitrogen. Yield data are average data for the 1976-81 wet season experiments at IRRI, and the Bicol, Maligaya, and Visayas Experiment Stations of the Philippine Bureau of Plant Industry (7).

Improvements in crop management save energy. For example, increasing the efficiency of N-fertilizer use in rice offers potential for enormous savings in N-fertilizer and thus in energy inputs. Improved timing and methods of N-fertilizer application can double N-fertilizer efficiency from a current 30% to 60%. Mudahar and Hignett (14) calculate that about 5.5 million t of nitrogen is applied to rice in Asia each year. If fertilizer efficiency improved to 45% (ie, by 50%), the savings in N would be about 1.4 million t, equivalent to 18 million barrels of crude oil. Alternatively if this N was applied to crops, the increase in Asian grain output would be at least 10 million t/yr.

The N-fertilizer example demonstrates how to improve the utilization efficiency of a stock energy source. Integrated pest management provides another example. Another approach is to replace, or at least substitute, part of these stock-based energy inputs with flow-based sources of these materials. Examples include using Azolla/*Anabaena azolla* complex, or possibly N-fixing blue-green algae; incorporating straw to supplement inorganic N-fertilizers; or substituting neem oil-based pesticides for inorganic ones.

Rice producers and processors can also more efficiently use the nongrain components of rice biomass, as per the examples in Table 4.

Unlike energy-efficient technology embedded in the rice seed, gains in energy efficiency through input or output management generally come to the farmer at some cost — in terms of his own labor, investment in new technology, inputs, or equipment. However, farmers respond to prices

Table 5. Disease and insect reaction of IRRI varieties.

Variety	Growth duration (d)	Disease and insect reaction (Philippines)[a]										
		Release date	BL	BB	GS	TG	BPH biotypes			GLH	SB	GM
							1	2	3			
IR5	140	1967	MR	S	S	S	S	S	S	MR	MS	S
IR8	130	1966	S	S	S	S	S	S	S	MR	S	S
IR20	125	1969	MR	E	S	MR	S	S	S	MR	MR	S
IR22	125	1969	S	R	S	S	S	S	S	S	S	S
IR24	120	1971	S	S	S	S	S	S	S	MR	S	S
IR26	130	1973	MR	R	S	MR	R	S	R	MR	MR	S
IR28	105	1974	R	R	R	R	R	S	R	R	S	S
IR29	115	1974	R	R	R	R	R	S	R	R	S	S
IR30	110	1974	MS	R	R	R	R	R	MR	MR	MR	S
IR32	140	1975	MR	R	R	R	R	R	MR	MR	MR	S
IR34	130	1975	R	R	R	R	R	S	R	R	MR	S
IR36	110	1976	R	R	R	R	R	R	MR	MR	MR	R
IR38	125	1976	R	R	R	R	R	R	MR	R	MR	R
IR40	120	1977	R	R	R	R	R	MR	S	MR	MR	R
IR42	135	1977	R	R	R	R	R	R	S	MR	MR	R
IR44	130	1978	MR	R	S	R	R	R	MR	MR	MR	S
IR46	130	1978	R	R	S	R	R	R	R	MR	S	S
IR48	140	1978	MR	R	R	R	R	R	S	MR	S	S
IR50	105	1980	MS	R	R	R	R	R	MR	R	MR	S
IR52	115	1980	MR	R	R	R	R	R	S	R	MR	–
IR54	120	1982	R	R	R	R	R	R	S	R	MR	–
IR55	110	1982	R	R	R	R	R	R	R	R	MR	–
IR58	100	1983	R	R	R	R	R	R	MR	R	MR	–
IR60	105	1983	R	R	R	R	R	R	R	R	MR	–

[a]BL = blast, BB = bacterial blight, GS = grassy stunt, TG = tungro. BPH = brown planthopper, GLH = green leafhopper, SB = stem borer, GM = gall midge. S = susceptible, MR = moderately resistant, R = resistant.

and profitability, not energy-efficiency ratios. Therefore, profitability as opposed to energy efficiency will remain the yardstick to evaluate the relevance of technical innovations. For example, it is unlikely that farmers in many parts of Asia will quickly shift to more energy-efficient systems of N-management, simply because it is not profitable for them to do so. However, if the price of N increases relative to labor and rice, there will be a strong incentive for farmers to adopt these innovations.

LIMITATIONS OF ENERGY ANALYSIS

The rates at which individuals or governments are willing to exchange goods and services (eg, rice, fertilizer, fuels, labor, technology) are not expressed in energy units. They are measured in money values. That is, governments, consumers, and farmers respond to prices, not joules. The issues from a research management viewpoint are which crops should be produced, where should they be produced, and what inputs should be used to produce them. Energy analyses provide no insights on these issues.

Proponents of energy analysis argue that prices do not lead to *optimal* (efficient? desirable? equitable?) energy use in agriculture or other sectors of economies. By implications, prices may not induce the optimal allocation of research resources or desired characteristics of technical innovations (1). Two reasons for dissatisfaction with the outcome of market forces are implied when energy ratios are advanced to provide superior values to guide resource allocation in agriculture (2). These are

1. prices of foods (output) are unsatisfactory guides to real (social) values; and
2. market prices of inputs do not adequately reflect their real (social) costs.

Using energy ratios as a criterion to adjust resource use toward a more socially *desirable* mix will not reduce misallocation due to either cause. Energy ratios can be used to identify opportunities for increased energy efficiency in agriculture. However, they cannot be used to evaluate alternatives relevant to an individual or to society. Eventually such analysis must be in terms of economics (6).

Problems of calculating energy ratios

To reiterate, the energy ratio (ER) is expressed as:

$$ER = O_i / I_i$$

where O_i is the sum of energy embodied in output O and I_i is the sum of energy embodied in input I. Several problems arise in estimating the components of ER. First, O_i may be measured at various stages in the production/distribution network — eg, at the farm gate, retail store, or on the household's dinner plate. Far more energy is normally consumed in marketing and preparing foodstuffs than in producing them on-farm. Normally, however, an ER for foodcrops is measured at the farm gate (eg, 16).

Second, energy embodied in O_i is variously measured in terms of total biomass production or more sensibly in terms of useful energy. Any aggregate estimate of energy o ignores that different components of biomass output different nutritional efficiencies, palatability, and pot uses. The ratio also ignores that the relevant measu output, at least of a foodstuff, is digestible energy, an gross thermal energy which is generally used to measu energy content of fuels or machines. Strictly, ER is rel only when the crop is produced primarily for er content. Thus, the ratio is misleading when a crop is g for its protein or fiber content.

When evaluating energy inputs (I_i), it is usual to inc upstream energy use to produce inputs, eg, fertilizer machinery, and their transport to the farm, as well as farm energy uses. At least three problems occur in aggre ing energy inputs to a common denominator:

1. difficulty in measuring energy embodied in facto production, for example, irrigation structures operation;
2. lack of distinction between renewable (flow) nonrenewable (stock) energies used in production; as a result
3. EA ignores the issues of relative scarcity of alterna energy sources.

Energy analysts generally agree on the energy value chemical and mechanical inputs. For example, aroun and 80 MJ are used to manufacture 1 kg N as ammonia as prilled urea (14). Similarly, the mass of energy emboc per kg of machinery in the seventies was about 85 MJ/ this figure has fallen from about 105 MJ/kg in 1950s (17).

There is less unanimity on how to incorporate la inputs into energy analysis. In some cases, energy cos labor have been measured as energy in food consumed (c portion of this, allocating some food intake to nonw activities); food energy plus energy costs of other goods a services required for maintaining the work force (or porti of this); or zero. It often makes little difference wh approach is used to calculate the EA of modern fo production systems because the ER of human energy usually a small proportion of the total input energy to a cr (Table 2). However, it was the high cost of human ener compared to chemical energy, which induced the substit tion of other forms of energy for human energy (e machines, agrochemicals) to increase labor productivity a profitability in agriculture.

The energy embodied in an input (assuming technolo constant) remains constant over time, irrespective of t current availability or level of unused stock. Therefore, E provides no insights into the optimal rate of use of resourc in finite supply (ie, *intergeneration equity*), or in the optim input mix required to produce a commodity at any point i time.

Measuring output in energy terms

If energy values as opposed to prices are accepted as th appropriate social value of foods, the implication is tha

nonenergy attributes of a food (aroma, taste, nutritional composition, convenience in preparation or storage, etc.) have no social value. The market preferences for high-quality rices over coarse-grain types demonstrates that this clearly is not the case. A more moderate view is that nonenergy attributes should play a lesser role in price formulation than they now do. What would be the impact if food prices were based on energy values in a situation where consumers still chose foods they preferred to eat, and farmers had some opportunity to respond to profitability when deciding what to produce? Simply, what is the congruence between freedom of choice and an energy-valued system of priority determination?

First, there would be a shortage of foods preferred by consumers for their nonenergy characteristics, and of foods relatively expensive to produce per unit of energy. Similarly, there would be a surplus of foods to which consumers assign low values for nonenergy characteristics and foods that cost little to produce per unit of energy.

This imbalance in supply, again assuming consumer preference, would lead to an increased market price for goods in short supply if the market were price-responsive. If official market institutions were not flexible, a parallel market would develop for goods in short supply with real prices higher than officially set. A dual exchange rate would exist. Either way, there would be pressure for prices of these commodities to rise above energy-determined prices. Alternatively, the prices of goods in surplus (induced by energy-determined values) would tend to fall — unless stockpiled by government or exported at prices lower than procurement cost. Another issue is whether governments would be able or willing to support storage or disposal costs of these surpluses.

The distortion in output prices caused by an energy-valued policy would have another impact probably regarded as undesirable by proponents of energy analysis. This policy would artificially increase the relative price of foods of high energy value, reducing consumers' incentive to substitute those foods — now in relative abundance — for those in short supply at energy-determined prices. In short, as long as consumers or producers could exercise any free will, the rigidities caused by an energy-based pricing system would be counterproductive to its objectives.

Energy valuing of inputs

The proponents of EA imply that nonenergy attributes of inputs should play a smaller role in price formulation than they now do. If only the energy value of an input were used as the criterion for comparative input valuation, then other attributes such as ease of storage or use, pollution potential, relative scarcity, etc., would be assigned no or low social value. Thus, one factor which provided the impetus to energy analysis in the early 1970s, ie, the combination of finite supplies, increasing scarcity, and increasing costs of fossil fuels, is not a construct of energy budgeting.

Disregarding limitations and problems of costing based on energy values, what would be the implication if input prices were also based on energy content? If such a policy were feasible, it would lead to an increase in price of inputs that are cheap per unit of embodied energy in the market place (eg, fertilizer). There would be a concomitant fall in the relative value of inputs such as labor which are comparatively costly in the market place per unit of energy. This would lead to an imbalance in input supply and demand. That is, the supply would tend to increase for inputs where energy supply prices had risen, while demand for these same factors would be reduced because of higher prices. The opposite effects would occur where relative values fell through energy pricing, ie, supply would diminish but demand would increase. The equilibrium exchange rate would be more likely to be settled on price-exchange terms as opposed to energy-exchange criteria.

PRICES AS RESEARCH GUIDES

The aggregation and valuation problems in energy analysis are partly overcome in economic analysis by using prices, as opposed to energy values, as weights. That is, output O_i is measured in value terms, ie,:

$$\text{Output value} = P_y Y_y \tag{4}$$

where P_y and Y_y refer to the prices and quantities of useful products produced by the process. The denominator of equation 1, ie, equation 3, is similarly evaluated as:

$$P_e X_e + P_l L_l \tag{5}$$

where P_e and X_e are prices and quantities of inputs, and P_l and L_l correspond to labor inputs. These prices reflect a) consumer's willingness to pay for the products in question at any point in production, ie, the equation overcomes biases when measuring inputs in energy terms, and b) the benefits producers are willing to forego by using an input in this rather than the next best use. When markets are imperfect, which is becoming more common with government intervention, shadow prices of inputs should be used to reflect the values of inputs and products from society's viewpoint. In summary, prices serve to homogenize heterogeneous inputs and infer value content to the resulting aggregate.

Energy ratios alone do not provide a sound basis for evaluating research strategies. Nor may response to market forces lead to socially efficient research or resource allocation. Market imperfections which result in market prices being inefficient guides to resource allocation include divergences between private and social benefits and costs; departures from free competition in product and factor markets; and government intervention through taxes, subsidies, or rationing. What is necessary are estimates of efficient market prices to guide evaluation of research alternatives. Another need is to get an estimate of social priorities which may diverge from those implied from a free-working market price formulation. Considerable progress has been made in quantifying divergences between

market (ie, private) and economic benefits and costs for efficiency analyses of research investment (3, 15). Assessing the equity and *quality-of-life* impacts of alternative investments remains illusive. However, Little and Mirrlees (11) and Squire and van der Tak (19) present methods to explicitly include equity considerations. Although it goes beyond the purpose of this paper, we believe the distributional impact of alternative innovations must be given greater weight in evaluating their social desirability than has commonly been the case.

ENERGY ANALYSIS IN PERSPECTIVE

Energy budgets, as characterized by ER, are not a definitive measure to direct priorities in rice research and policy formulation, and certainly not when developing farmer recommendations. We argue that prices are a preferable set of value weights to determine resource distribution and research priorities. Yet, economists cannot claim that they have provided clear leadership in this domain until more attention is given to estimating shadow prices for those resources used in rice production. Such information will facilitate planning research priorities, and examining the implications of policies for reducing the gap between market and social prices of these inputs.

Shadow-price estimates are frequently made in terms of present, if not past, relative prices. But today's research is the basis of tomorrow's technology. The challenge, therefore, is to be forward-looking and to base economic analysis on the best judgments of what future relative prices will be. IRRI does not have a comparative advantage in this type of research. Collaboration with institutions such as the International Food Policy Research Institute and Food and Agriculture Organization may be the most efficient way for IRRI to gain access to this type of information and to embed it in its decision-making process.

It is naive to imply that a concern for energy efficiency is not a legitimate concern of policy makers, research administrators, and researchers. Clearly, conjunctive use of energy and economic analysis is desirable and possible when formulating research priorities. For example, rather than examining ER's of alternative production practices, IRRI may focus on the analysis of disaggregated energy inputs. We should examine those factors where total energy inputs are high, and where, from a technical viewpoint, there are opportunities for increasing energy and economic efficiency.

IRRI has a responsibility to focus on energy efficiency in rice technology. However, in doing so it must not lose sight of the fact that the vast majority of Asia's rice farmers make production decisions based on tradition and the prices they observe in the market. Therefore, the objective of deve more cost-efficient technology must be uppermost already is occurring. The rise in energy cost since 1 has pushed energy-wasteful inputs out of the rea interest of farmers. Farmers have responded to the c in relative prices in the 1970s by adjusting their fa operations in light of changing relative input and pr prices. Generally, farmers are more responsive t nuances of the market than are researchers.

Policy makers still wish to modify the use rate of resources from that level implied when legitimate mar shadow prices are used as guidelines. Therefore, IRR consider initiating (or become associated with) res examining policy alternatives to induce farmers to a more energy-efficient rice production systems than w prevail without government intervention. These in ments may be based on subsidies or taxes, for examp effect what is politically regarded as desirable chang resource use and income distribution.

CONCLUSION

Rice supplies in Asia must continue to grow by some 39 just to maintain the nutritional status of the world's eaters. The use of modern support energies has been dec in generating past output growth and will remain so for foreseeable future. Any decline in the provision of s modern support energy will lead to reduced productior increases in the relative price of food staples, and as a res increase poverty, malnutrition, and starvation. The a cultural development goals of the Third World cannot met in the near future without improved varieties, m irrigation, more use of fertilizers and pesticides, and in so cases, more mechanical power. IRRI research must, the fore, continue to work toward increasing the technical a economic efficiency of rice production systems tempered equity considerations. IRRI must also continue to expl technological options which allow greater substitution flow energy for fossil (nonrenewable) energy.

Research designed to increase input and output efficien and reduce reliance on nonrenewable energy sources off large potential payoffs to Asian rice producers and co sumers. Energy budgets can highlight the distribution a use patterns of energy resources in production and co sumption, and can complement and augment decisio relating to resource use now and over time. Howeve economic analysis should continue to be the screenir mechanism to evaluate technically valid alternatives ar identify those financially viable for farmers.

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Appendix 1. Energy conversion rates used in energy analysis of rice production.[a]

	Unit	Energy value/unit	
		Kcal (100)	Megajoules
Human labor	h	.25	1.046
Animal labor	h	1.85	7.706
Seed	kg	2.95	12.343
Fertilizer	kg N	19.37	81.046
Insecticide and herbicide	kg ai	25.55	106.904
Machine	kg	22.00	92.050
Fuel	litre	9.15	28.326
Irrigation	ha-cm	11.00	46.025
Yield	brown rice	2952	12.35

[a]Transformation coefficients may multiply the errors incurred in measuring inputs and yield because of the assumption that inputs are homogeneous across systems, e.g., that animal-hours in the Philippines are equivalent to those in Bangladesh. Fertilizer is another example. Without knowing how the fertilizer was manufactured, we assume an equivalent upstream energy content in all cases. This is clearly difficult to support.

Appendix 2. Equivalent energy units (14).

Joule (abbreviated as J) is the SI unit of energy. It is defined as the work done when a force of one Newton acts through 1 m.

Multiples of the joule are:

1 Kilojoule (KJ) = 10^3 J
1 Megajoule (MJ) = 10^6 J
1 Gigajoule (GJ) = 10^9 J

Btu. One British thermal unit (Btu) refers to the heat (energy) required to raise the temperature of 1 lb of water by 1°F. Approximate Btu conversion factors to the joule are:

1 MJ = 0.948 x 10^3 Btu
10^6 Btu = 1.055 GJ = 10 Therm

kcal. One calorie refers to the heat required to raise the temperature of 1 g of water by 1°C. One kilocalorie, referred to as kcal (or a Calorie), is 1,000 calories. kcal equivalents to joules are:

1 MJ = 0.239 x 10^3 kcal
1 kcal = 3.968 Btu

Energy equivalents of common fuels and fertilizer:

1 US barrel of crude oil = 6.12 GJ
1 litre of gasoline = 35.1 MJ
1 litre of diesel = 39.5 MJ
1 mt of N = 12.77 barrels of crude oil
1 kg N (urea) = 80 MJ

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