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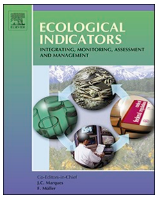

Original Articles

Energy efficiency of agricultural systems in the southwest coastal zone of Bangladesh

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ABSTRACT

Indicators for energy-use efficiency and levels of CO_2 emissions were used to evaluate and compare a range of agricultural systems in coastal Bangladesh in order to identify the most energy efficient system. Using data collected by the authors, five different food production systems involving both agriculture and aquaculture in the coastal area of Bangladesh were studied. In particular, *Bagda* (shrimp), *Bagda*-rice, rice, *Galda* (prawn)-rice-vegetable, and traditional practice-based agricultural systems were thoroughly investigated. The findings revealed that the *Galda* (prawn)-rice-vegetable-based integrated agricultural system was the most energy-efficient system and released less CO_2 than the other four systems.

1. Introduction

Energy use and CO_2 emissions within agricultural systems are crucial for ensuring the sustainability of food production systems in an era of climate change, overpopulation and food insecurity. Food systems around the world consume about 30% of all available energy (FAO, 2012). Agricultural production systems absorb a major portion of this energy use. Agriculture is also considered a primary greenhouse gas (GHG) emitter and is responsible for one-third of the world's GHG emissions (Gilbert, 2012). However, agriculture not only utilizes a diverse range of energy types but also can supply bio-energy (McMichael et al., 2007) and other multifunctional services (FAO, 2013). The interconnectedness between energy and the practices employed within agricultural systems is widely recognised (Best, 2014) and in the present world context, it is vital that food production be efficient and resilient in terms of consuming the limited energy resources. In order to face the challenges of ensuring food security, adapting to climate change and mitigating environmental degradation, the need to strive for efficiency is paramount at all levels, from farms to global food systems (FAO, 2012).

The processes of food production require a number of inputs including natural, human, social, physical and financial capital. The combination of these types of capital, how much and how they are used, is important in considering the success of the food production process. Inefficient operations are one factor that makes an agricultural system unsustainable and can therefore hamper overall global sustainability (Tilman et al., 2002). Along with natural inputs (i.e., sunlight, rain and soil nutrients), the agricultural process requires varieties of anthropogenic physical inputs including labour, seeds, agrochemicals and machinery for the essential purposes of land preparation, irrigation, harvest, post-harvest processing and transportation of agricultural inputs and outputs.

An integrative assessment of the efficient use of various inputs for the sustainability of food production systems requires a common unit that can be used to measure all the different aspects of agricultural systems. For this purpose, every physical input and output of agricultural production can be expressed in energy terms, using joules as the basic unit.

Energy efficiency can be measured using different metrics that are based on energy consumption and production during the growing of a crop (vanLoon et al., 2005). Energy is an encompassing term, especially important in food production, in that the embodied energy of inputs (energy required to produce these inputs) can be compared with the energy of outputs (caloric value of the food produced) (vanLoon et al., 2005). Because it reaches beyond agricultural boundaries and includes all the steps of crop input production, energy analysis is a useful indicator of environmental and long-term sustainability (Alluvione et al., 2011).

To be sustainable, all resources required for agriculture (human, animal and material) should be used in a way that is not wasteful and

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Table 1
Description of the agricultural systems.

	**S:** This system is dominated by intensive cultivation of Black Tiger shrimp (*Penaeus monodon)*, locally called *Bagda Chingri*, with some rice. Transplanted *Aman* rice is the principal crop during and after the rainy season (the *kharif-2* season: July to October), a time when water salinity is low. *Aus* rice and *rabi* (dry, winter: October to March) seasonal crops may grow in non-saline upland areas (typically at 1 to 2 m above the shrimp-producing tidal flats). Betelnut, coconut, vegetables, and local fruits can be grown in homestead areas.
	**SR:** *Bagda* is also cultivated intensively, and during the low-salinity period from August to December a salt-resistant type of *Aman* rice is cultivated in elevated parts of the fields. Usually, the homestead area is used for growing rice as well as *rabi* crops and vegetables both for personal consumption and for commercial purposes. In homestead areas, betelnut, coconut, and local fruits can be grown.
	**R*:*** Rice is widely cultivated and is rain-based during the monsoon season. During winter, *boro* rice is grown with irrigation. In the *kharif* season (April-September), jute (*Corchorus)*, sugarcane *(Saccharum*), and sesame (*Sesamum indicum*) are grown in addition to rice.
	**I:** Rice, fresh water prawn (*Macrobrachium rosenbergii*, locally called *Galda Chingri*), a variety of fish, and vegetables are cultivated in and around the same *gher*. Tilapia and carp are prominent fish species, and vegetables including water gourd, lady's finger, squash, bean, amaranth, and cucumber are common. It is typical to cultivate *galda* (along with fish in some cases) and rice together in the same field during the winter season. On the dikes that surround *ghers*, vegetables are grown throughout the year.
	**T:** *Aus*, *aman* and *boro* rice are cultivated in sequence throughout the year. Pulses such as grass pea, beans, lentils, groundnuts, and mustard are important components of the agricultural system. Recently *boro* rice, potato, and watermelon cultivation and productivity have increased. Some farmers are practicing intercropping such as chili or okra plus sweet gourd or potato plus bitter gourd.

Source: Field study, 2011; Talukder et al. (2016).

that maximizes output per unit input. An agricultural system can be deemed highly efficient if a small supply of inputs, especially non-renewable inputs, results in excellent productivity (vanLoon et al., 2005). Effective energy use in agricultural systems is one of the conditions for sustainable agricultural production, since it provides both financial savings and environmental benefits (Sefeedpari et al., 2012). Efficient use of energy helps to achieve increased productivity and contributes to the economy, profitability and competitiveness of rural communities (Omid et al., 2011).

While the need to consider energy is of central importance, other components of the agricultural system also come into play and must be accounted for. Among many energy inputs, synthetic fertilizers such as those that supply nitrogen (N) play a major role in increasing food production. However, the application of N in agriculture has both beneficial and detrimental effects on ecosystems and human health and has led to the degradation of air and water quality, contributes to acid rain, causes ozone depletion and sometimes destroys natural ecosystems (Prasad, 1998; Tilman et al., 2002; Dobermann and Cassman, 2004; Gregory et al., 2005; Conley et al., 2009). Like N fertilizer, phosphorus (P) not only helps to raise the fertility level of formerly poor soils but also causes contamination or dilution and is harmful as a polluting agent of surface water (Schröder et al., 2011). To go further, there are environmental concerns concerning the use of all other energy-consuming inputs, including pesticides, fuels and so forth. The possible negative side-effects of agrochemicals make up another reason why it is prudent to ensure their efficient (hence not wasteful) use.

Agriculture in coastal Bangladesh is under great pressure to supply food to meet the needs of the growing population in the area. The coastal region is subject to climate change impacts, frequent cyclones and floods, land scarcity, lack of freshwater, waterlogging, declining soil quality, decreasing ecosystem services and anthropogenic pollution (Talukder et al., 2016). During the past several decades, various types of agricultural systems have been developed, and these must not only produce sufficient food for the growing population but also be eco-efficient for long-term sustainability of the systems. Proper management of agriculture is essential as an adaptation strategy in coastal Bangladesh. Among the agriculture practices being followed, there is competition for land use between aquaculture and agriculture (Islam, 2006). Considering all these factors, the primary objective of this study was to assess and compare energy efficiency in various agricultural systems of coastal Bangladesh. The secondary objective was to calculate CO_2 emissions from the various agricultural systems.

2. Materials and methods

In this research, an indicator-based methodology was used to assess energy efficiency, and descriptive data obtained from various types of primary and secondary sources were used to support the findings. *Bagda* (shrimp)-based agricultural systems (S), *Bagda*-rice-based agricultural systems (SR), rice-based agricultural systems (R), *Galda* (prawn)-rice-vegetable-based integrated agricultural systems (I) and traditional practices-based agricultural systems (T) were selected for examination based on discussion with local partners and backed up by a review of the literature that describes agricultural practices followed in the area. The data for this study were collected in 2011 and pertain to the cropping season of 2010.

2.1. Description of the agricultural systems

All of the study sites examined are located between 22.3500°N and 90.6525°E. The agricultural systems consisting of S, SR, and I are located in Shyamanagar *Upazila,* Kalijang *Upazila* and Dumuria *Upazila*, respectively. Each of these *Upazilas* (local administrative units) is located in the Ganges tidal floodplain of the southwest coastal belt. In addition, R is situated in Kalaroa *Upazila*, further north in the floodplain while T is located in Bhola sadar *Upazila* in the more recently formed Meghna estuarine floodplain east of the other sites (BARC, 1996; Rashid, 1991). Agriculture in all of the sites is affected by the tropical monsoon climate called Koppen A_m (Kottek et al., 2006). A brief description of the agricultural systems and their associated products is presented in Table 1. Rice, the staple food of the local people, is cultivated in each location. Rice and other crops occupies the entire agricultural area in R and T, while in S, SR and I, one-third to a-half of the total agricultural land is dedicated to shrimp/prawn cultivation.

2.2. Data collection

Primary data were collected by deploying household questionnaire surveys with responses obtained via face-to-face interviews with 212 sampled farmers in the study areas. After field investigation, observation and discussion with the local experts, it was found that the farmers were practicing homogenous agriculture systems in the study sites. A pilot survey was carried out to develop a final version of the questionnaire. Key criteria for selection of the study sites included the dependency of the population for livelihood on local agriculture, positive attitude of the community, community cohesiveness, time-tested and knowledgeable farmers and eagerness to take part in focus group discussions (FGD), as well as support from local NGOs and local government administration.

To save time and money, purposeful random sampling (Cohen and Crabtree, 2006) was carried out to select 40, 60, 59, 22 and 26 representative households from S, SR, R, I and T, respectively. The households within each site were selected through stratified random sampling (Ahmed, 2009) and represented landless labourers and farmers, ranging from those with marginal holdings to those who cultivate more than 2 ha (BBS, 2010).

Various documents produced by the Government of Bangladesh and NGOs were also consulted as sources of secondary data. In addition to the individual interviews and secondary data collection, 5 focus group discussions and 20 key informant interviews were conducted to support and validate the data collected. Information related to agricultural products like rice, shrimp, vegetables and other crops as well as inputs like seeds, fertilisers, pesticides, human labour, bullock power, machinery and fuel was collected to calculate energy and economic efficiency.

2.3. Techniques used to calculate energy efficiency and CO_2 emissions

Energy equivalents for various materials and processes (Appendix I and II) were used to calculate individual input and output energy values. Input energy was classified into renewable and non-renewable forms. Renewable energy covers seeds, fish feed consisting of plant- and animal-based components, human labour, bullock labour and cow dung fertilizer. Non-renewable energy includes agrochemicals including fertilizers, pesticides and lime, diesel and machinery. In the case of output energy, only the energy embodied in the crops and fish products was considered. These values were used to calculate the land use-efficiency, net energy gain, energy ratio, energy productivity and non-renewable energy ratio (Table 2) with the help of Excel spreadsheets. In addition, analogous costs and product values were obtained, and financial efficiency indicators were also calculated for comparison purposes.

In this paper, land use efficiency is defined as the amount of energy produced in a given area of land. The difference between the gross energy output and the total energy used in producing the crop is net

Table 2
Standard equation used for calculation of parameters of energy efficiency.

Parameters of energy efficiency		Formula	Ref.
Land use – efficiency	=	Output energy (MJ)/Total land (ha)	c
Net energy gain	=	Output energy (MJ ha^{-1}) − Input energy (MJ ha^{-1})	a, c, d, e, f
Energy ratio	=	Output energy (MJ ha^{-1})/Input energy (MJ ha^{-1})	a, c, d, e, f
Energy productivity	=	Crop yield (kg ha^{-1})/Input energy (MJ ha^{-1})	a, c, d, e, f
Non-renewable energy ratio	=	Output energy (MJ ha^{-1})/Non-renewable energy input (MJ ha^{-1})	c

Sources: [a]Mohammadi et al. (2010); [b]Khan et al. (2009); [c]vanLoon et al. (2005), [d]Mandal et al. (2002); [e]Mani et al. (2007); [f]Rathke et al. (2007).

energy gain. Energy ratio is the ratio between crop energy produced and energy used in the production of the crop. Energy productivity is a measure of the amount of crop produced by a given amount of energy input (Sefeedpari et al., 2012). The non-renewable energy ratio takes the same form as the (overall) energy ratio but considers only non-renewable energy used in the production. Among the selected energy efficiency indicators, energy ratio has been the most widely used; it includes measures of all types of energy used in the production of crops (input energy) and the amount of food energy (output energy) contained in the various crops produced. Obtaining a comprehensive assessment of energy inputs and outputs allows the comparison of energy efficiency across the selected agricultural systems to determine how they stack up. Energy ratio is one metric that defines the sustainability of an agricultural system and can be useful to agricultural planners as well as to individual farmers.

To calculate CO$_2$ emissions from crops, the Cool Farm Tool (CFT) was employed (CFA, 2018). The computer program for executing CO$_2$ emissions by CFT, along with a manual is available online (CFA, 2018). In the absence of more site-specific information, to estimate the CO$_2$ emissions from aquaculture, the coefficients 3.0799 kg and 0.6033 kg CO$_2$ per 100 kcal production of shrimp and fish respectively (UNEP, 2008) were used.

3. Results and discussion

In the southwest coastal area of Bangladesh, land is used for both agricultural crops and for shrimp farms (*ghers*), which are flooded areas contained by embankments. The high demand and price of shrimp and prawn in national and international markets, as well as the construction of coastal polders, have influenced the traditional fishery in this part of the country and led to the conversion of land into widespread intensive shrimp farming (Islam, 2006). Satellite image analysis showed there has been an overall 30% increase in the area devoted to *ghers* during the last 13 years, whereas agricultural land and associated natural vegetation decreased by 48% and 3%, respectively (Khan et al., 2015). Detailed field investigations revealed that the proportion of land assigned to aquaculture increased as one moves southward into the more exposed coast. This was evident in agricultural systems S and SR that are very close to the coastal areas, less so in I and R, and did not occur at all in T (Table 3). The location of T is an exception. Specifically, traditional agriculture is situated within the exposed coast created by recently deposited sediments where the land is devoted only to agriculture.

Shrimp is harvested throughout the year. Usually only one crop of rice is taken in the winter season in S and SR, while a second crop can be grown in the monsoon season in the other areas. In all of the areas, the productivity measured as total yearly yield (kg ha^{-1}), was found to be much greater for rice than for shrimp (Table 3).

The observed annual yields of rice bracketed the average yield (4000–6000 kg ha^{-1}) for Bangladesh in the same year, whereas the yield of modern rice varieties can reach as high as 10,000–11,000 kg ha^{-1} (Basak et al., 2012). The sizes of the harvest varied among the agricultural systems depending on the local environment and the diverse methods of crop management. Shrimp yields were low in comparison with those achieved in the semi-intensive shrimp farms of some Asian countries like Indonesia (1479 kg ha^{-1}), Malaysia (4693 kg ha^{-1}), Vietnam (662 kg ha^{-1}), India (500–2374 kg ha^{-1}) and Sri Lanka (5040 kg ha^{-1}, Ling et al., 1999), although a yearly average of 600 to 700 kg ha^{-1} of shrimp and 450–550 kg ha^{-1} prawn have been measured in some well-managed *ghers* of Bangladesh (Hossain, 2015).

Table 4
Energy efficiency in the agricultural systems.

Parameters of energy efficiency	Agricultural systems				
	S	SR	R	I	T
Land use efficiency (MJ ha^{-1})	8000	21,000	114,000	74,000	63,000
Energy gain per ha (MJ ha^{-1})	−6000	−5800	57,000	39,000	32,000
Energy ratio	0.55	0.78	2.03	2.11	2.09
Energy productivity (kg MJ^{-1})	0.05	0.06	0.16	0.17	0.16
Non-renewable energy ratio	0.82	0.92	2.25	2.89	2.48

Note: Rice, other crops and shrimp/fish are considered to calculate energy efficiency.

Combining the energy value of the produced rice and shrimp and measuring the energy content of all the inputs used in production, we have calculated the various parameters of energy efficiency for total food production in each of the agricultural systems (see Table 4 or Fig. 1). Among the performances shown by the various metrics, agriculture carried out in R, I and T stood out as exhibiting good energy efficiency in all categories, with I having the highest values in those metrics involving output/input ratios (see Table 4 and Fig. 1). Yield of rice was also highest in this area (Table 3). R and T similarly showed good efficiency and, in fact, agriculture in R showed the best land use efficiency and energy gain. S and SR fared much more poorly in all efficiency measures and had negative energy gain values and energy ratios less than 1, indicating that more energy went into production than was gained in the products. This poorer efficiency reflected the greater energy intensity of inputs for producing shrimp and other aquatic products compared with inputs for land-based agriculture. These values (Table 4) all relate to production of the primary (food) product only. If one includes the energy value of the secondary products (in the case of rice, the stalks), the measured energy efficiency in production is, of course, greater. For example, assuming that the mass of stalks of the rice plant is about 1.5 times the mass of the grain, the energy ratios increase by a factor of approximately 2.5. However, all the energy data reported in this paper relate to the primary product of food for human consumption.

While the principal products from agriculture in this area were rice

Table 3
Land use, yield of rice and shrimp/prawn/fish in the agricultural systems.

Parameters	Sub parameters	Agricultural systems				
		S	SR	R	I	T
Land use	Land use for rice and other crops (ha)	10.5 (11.2%)	37.9 (19.3%)	44. 8 (87.8%)	8.6 (35. 6%)	49.0 (100%)
	Land use aquaculture* (ha)	83.3 (88.8%)	158.6 (80.7%)	6.2 (12.2%)	15.6 (64.4%)	–
	Total land use (ha)	93.8 (100%)	196.4 (100%)	51.0 (100%)	24.3 (100%)	49.0 (100%)
Yield	Yield of rice (kg ha^{-1})	2260	4410	5230	6510	2860
	Yield of shrimp/prawn/fish (kg ha^{-1})	233.3 (shrimp)	383.3 (shrimp)	32.1 (only fish)	321.6 (prawn)	–

Note: *Aquaculture represents shrimp and fish in S and SR, fish in R and prawn and fish in I.

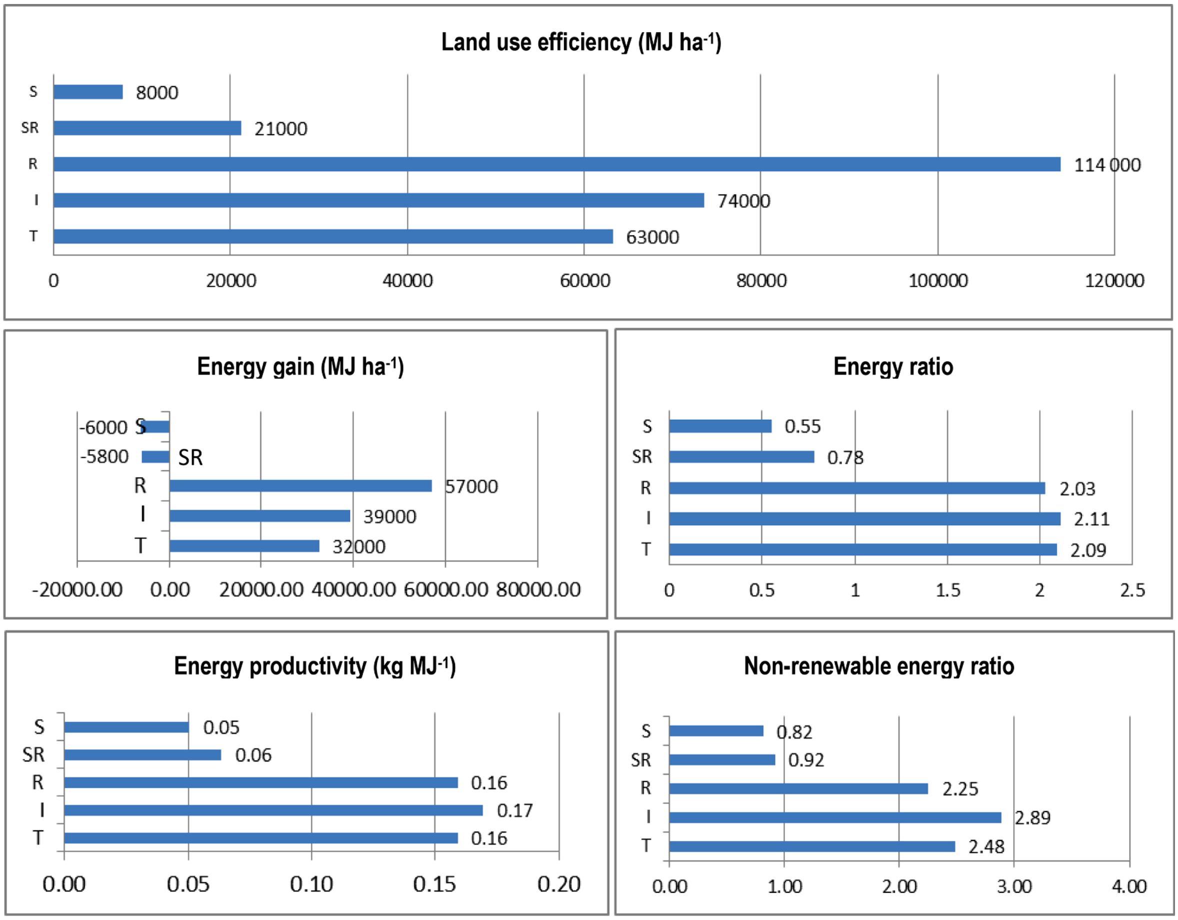

Fig. 1. Energy efficiency in each of the agricultural systems.

and shrimp, other crops, especially pulses, potatoes, and other vegetables, wheat, and mustard, were also produced on a small scale, usually on embankments or in upland areas around homesteads. Because no or few energy inputs (other than human labour) were used in growing these vegetables, mostly for home consumption, input energies were usually negligible. The resulting energy ratios when these crops were included with rice are somewhat greater than those for rice alone.

Previous researchers have similarly calculated land use efficiency in energy terms, although it was not specified whether they included the entire crop or the primary product (grain) alone. For example, AghaAlikhani et al. (2013) showed that the net energy gain of traditional and mechanized rice production systems of Mazandaran province of Iran are 51,870 MJ ha^{-1} and 50,506 MJ ha^{-1}, respectively. Pishgar-Komleh et al. (2011), also in Iran, calculated the net energy gain for rice production as 21,008 MJ ha^{-1}. In another Iranian study, Mansoori et al. (2012) calculated net energy gain for organic rice production to be 79,351 MJ ha^{-1}, higher than for conventional rice production (15,802 MJ ha^{-1}). Chaudhary et al. (2006) found the highest net energy gain in rice–wheat (102,865 MJ ha^{-1}) among six cropping systems in India: rice–wheat, rice-mustard green gram, rice-vegetable pea-wheat-green gram, maize-vegetable pea-wheat, pigeon pea-wheat and soybean-wheat.

Measured as a ratio of output over input, energy efficiency has been determined in a number of other studies on the production of rice and other crops in Bangladesh and elsewhere the world. In Bangladesh, small rice-producing farms ranging from 0.61 to 1.0 ha yielded higher energy ratios (4.14) than larger ones (Pishgar-Komleh et al., 2011). Cherati et al. (2011) calculated the energy ratios for rice production in traditional and semi-mechanized farms in the Mazandaran Province of Iran and found these to be 3.00 and 3.08, respectively. Cherati et al. (2011) used a complete energy budget including diesel fuel, gasoline fuel, human labor, agricultural machinery, fertilizers, herbicides, fungicides, seed and estimates of canal irrigation energy as input energy and rice production as output energy. In the U.S. Midwest, Gelfand et al. (2010) found even greater energy ratios, 10 and 16, for conventional and no-till food production systems respectively, considering agro chemicals, seeds, field operations and agricultural machinery maintenance as input energy. Comparing energy use in conventional and integrated arable farming systems (including multi-functional crop rotation, minimal soil cultivation, integrated nutrient management, integrated crop protection, ecological infrastructure management) in the UK, Bailey et al. (2003:241) concluded that in terms of "energy used, the integrated system appears to be the most efficient. However, in terms of energy efficiency, energy use per kilogram of output, the results were less conclusive." Clearly, even the best-performing production systems our study did not achieve the high productivity shown in these other studies.

Responses to the detailed questionnaire revealed that rice production depends substantially on non-renewable energy use. It is noteworthy that non-renewable chemical fertilisers and pesticides make up the greatest share (68% to 84%) of total energy inputs. Considering the total land use in each area, average rates of fertilizer addition (sum of urea, triple super phosphate, potash, gypsum and boron) ranged from 265 kg ha^{-1} in S to 1268 kg ha^{-1} in R, with other values in the 400 to 600 kg ha^{-1} range. For rice, only urea was used, at rates of 320 kg ha^{-1}, 471 kg ha^{-1}, 633 kg ha^{-1}, 595 kg ha^{-1}, 347 kg ha^{-1} in S, SR, R, I and T, respectively. In none of these cases was animal manure applied to fields producing rice. While the large value of chemical fertilizer applied in R reflected the lack of training for farmers in the area of proper agricultural practices, it did result in the highest yields of rice. Farmers in S were reluctant to invest in fertilizer because rice production was already limited by the soil and water salinity in the area. Diesel for irrigation was also a significant component of the non-renewable energy sources, representing 2%, 12%, 19%, 13% and 5% of the total non-renewable energy of S, SR, R, I and T, respectively. In S, R and T, farmers also largely depended on rain water and surface water for irrigation. Inefficient traditional agricultural practices along with the lack of knowledge about efficient energy use, dearth of research and development and poor government supervision are some of the causes of the inefficient use of energy in the studied areas.

While not applied when growing rice, cow dung was used in S, SR and I for the preparation of the *gher* at rates of 180 kg ha^{-1}, 209 kg ha^{-1} and 185 kg ha^{-1} respectively; the cow dung, in a dry form, supports the growth of algae as food for the shrimp. The greatest use of renewable energy was found in S, SR and I. S obtained 50% and 34% of its renewable energy from cow dung and fish feed, respectively. Farmers used greater amounts of cow dung in S than in any other area because of the need to rejuvenate the *ghers* after the devastation caused by cyclone Aila in 2009. The least renewable energy, only 6% of the total, was used in R. In I, 55% and 40% of the total renewable energy comes from bullock labour and seeds, respectively. Both T and R used 7% renewable energy in the form of human labour. Table 5 presents the percentage breakdown of the different forms of renewable energy as well as land use and energy efficiency information for rice and fish in each agricultural system.

Human energy used in production itself was small compared to other forms of energy; this was true even when considering only renewable energy which is comprised of seed, fish feed and bullock labour. Human energy required for land preparation, weed and pest management, irrigation and harvesting crops, ranged between 76 and 114 person days ha^{-1}. It is interesting, however, that human labour intensity per hectare in aquatic areas was about half that of land-based crops. In shrimp cultivation, human labour was limited to *gher* preparation, security of the *gher* and during shrimp harvesting time, whereas in diversified agriculture human labour was used throughout the cropping season.

The non-renewable energy ratio (Table 4) uses only non-renewable energy sources including fuel, machinery and chemicals, when calculating energy inputs. The efficiency measures are based on all the inputs and outputs within each food production system, and it is clear that the separate values related to rice and shrimp will be significantly different.

The various energy efficiency values given in Table 5 refer to the five agricultural systems, and include input and output values and calculated indicators for shrimp, rice and other crops. Where shrimp is dominant, the overall energy efficiency values are much poorer. Other studies have shown similar values. Rahman and Barmon (2012) in their study showed that in joint agricultural systems (freshwater prawn, fish and HYV rice) the energy efficiency ratio was 1.72. In this study, it is evident that in energy terms, shrimp production is a much less sustainable activity. In each case at the three sites where shrimp were being produced, the energy value of the product was around one-tenth that of the inputs required, including chemical fertilizers, cow dung and, very significantly, disease control chemicals. Along with cow dung, chemical fertilizer like urea is used to grow algae in the *gher*. Chemicals like sodium thiosulfate were utilized to clarify the water. Chlorine and Acme's zeolite (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO) were also used to purify the water and prevent shrimp disease (Shamsuzzaman and Biswas, 2012). Most of the chemicals were for control of White Spot Syndrome, a viral infection of shrimp. The disease is highly lethal and contagious, killing shrimps quickly. Outbreaks of this disease can wipe out the entire population of a *gher* within a few days. According to farmers and *upazila* fisheries officers, there is no available treatment for this disease. However, farmers occasionally use "Aqua Fresh" to minimize the effects of disease. According to the farmers, it helps to clean *gher* water.

There are situations in which efficiency has been measured in terms of energy productivity, that is, kg of product produced per MJ of energy in inputs. Cherati et al. (2011) showed that the energy productivity of the traditional and mechanized rice production systems of the Mazandaran province of Iran was 0.111 and 0.116 kg MJ^{-1}, respectively. Esengun et al. (2007) documented a 1.0 kg MJ^{-1} energy productivity rate for stake-tomato in the Tokat province of Turkey. Yilmaz et al. (2005) estimated the energy productivity of cotton as 0.06 kg MJ^{-1}. Erdal et al. (2007) documented the energy productivity of sugar beet as 1.53 kg MJ^{-1}. Mansoori et al. (2012) showed that the average energy productivity of rice in conventional and organic systems was 0.08 and 0.18 kg MJ^{-1}, respectively. In the present study, the results ranged from 0.051 to 0.169 kg MJ^{-1}, with the higher values found in the areas primarily producing rice.

Table 5

Land use and energy efficiency for rice and shrimp/prawn/fish and percentage of different forms of renewable energy for agricultural systems.

Land use and energy efficiency parameters		Agricultural systems				
		S	SR	R	I	T
Land use efficiency of rice (MJ ha-1)		60,200	102,000	130,000	204,000	63,300
Land use efficiency of fish (MJ ha-1)		1170	1920	160	1610	–
Energy output from rice (MJ) [without stalks]		6.32×10^5	38.5×10^5	58.1×10^5	17.6×10^5	31.0×10^5
Energy input in rice (MJ)		3.5×10^5	21.9×10^5	29.0×10^5	5.11×10^5	15.0×10^5
Energy ratio for rice production		1.81	1.76	2.00	3.44	2.07
Energy output from rice and other crops (MJ) (without stalks)		6.32×10^5	38.5×10^5	58.1×10^5	17.6×10^5	31.0×10^5
Energy input in rice and other crops (MJ)		3.5×10^5	21.9×10^5	29.0×10^5	5.11×10^5	15.0×10^5
Energy ratio for production of rice and other crops		1.81	1.83	2.03	3.45	2.09
Energy output from Shrimp/fish (MJ)		9.7×10^4	30.4×10^4	–	2.5×10^4	–
Energy input in Shrimp/prawn/fish (MJ)		9.5×10^5	31.0×10^5	–	3.1×10^5	–
Energy ratio of Shrimp/prawn/fish		0.10	0.10	–	0.08	–
Energy output from rice + other crops + Shrimp/prawn/fish (MJ)		7.2×10^5	41.1×10^5	58.8×10^5	17.5×10^5	31.3×10^5
Energy input from rice + other crops + Shrimp/prawn/fish (MJ)		13.0×10^5	53.0×10^5	29.0×10^5	8.3×10^5	15.0×10^5
Energy ratio for production of rice + other crops + Shrimp/prawn/fish		0.55	0.78	2.03	2.11	2.09
Other parameters						
Percentage of different forms of Renewable energy	Seed	7	11	40	12	41
	Fish Feed	33	25	–	41	–
	Cow dung	50	52	–	26	–
	Bullock Labour	6	9	54	16	53
	Human Labour	2	3	7	4	7
Human labour (man day)/ha in rice		156	178	128	178	116
Human labour (man day)/ha in shrimp		26	32	0	95	0

Table 6
Economic efficiency indicators for rice and shrimp compared with equivalent energy efficiency indicators.

Parameters	Agricultural systems							
	S		SR		R	I		T
	Rice	*Gher*	Rice	*Gher*	Rice	Rice	*Gher*	Rice
Land use for food production(ha)	10.5	83.3	37.9	157.6	44.8	8.63	15.6	49.0
Total Production(t)	42.9	19.4	261	60.6	395	119	5.03	211
Market value ($)	10,900	73,600	67,600	292,000	107,000	35,600	30,600	38,900
Expenditure ($)	7000	48,400	38,200	123,000	39,600	8300	16,000	19,500
Economic efficiency ratio	1.56	1.52	1.77	2.38	2.69	4.3	1.91	1.99
Net Economic gain ($/ha)	374	300	777	1080	1500	3160	933	395
Energy efficiency ratio	1.81	0.1	1.83	0.1	2	3.44	0.08	2.07
Net energy gain (MJ/ha)	26,900	−10,200	43,800	−17,700	64,800	144,000	18,200	–

While all the efficiency measures shown here indicate that production of shrimp was an energy-inefficient process, it is important to recognize that shrimp is not produced and consumed primarily as an energy-supplying food commodity. Rather, it is a specialty food generally eaten in relatively small quantities, valued for its culinary properties and as a supplier of good-quality animal protein and other important micronutrients. As such, it is a product that commands a high price in the local and especially the international market. Table 6 displays the efficiency of production in terms of cost, measured as economic ratio and economic gain, and compares this to efficiencies for rice. For additional comparison, the equivalent energy efficiency values are also given.

In all cases, the two measures show that shrimp production was economically a positive operation, but there were significant differences between the three sites where shrimp were cultivated. The very low values, especially for S (1.53) are indicative of large financial expenditures (labour, chemicals, breeding stock etc.) along with limited yields, giving only limited gain to the farmers. In S, the production of rice had declined due to increased salinity resulting from massive shrimp cultivation and being in close proximity to the sea. Shrimp has taken over and can be highly profitable, but its production and profitability have been adversely affected by the White Spot Shrimp Virus (WSSV) which has devastated the shrimp population throughout parts of the southwestern coastal region since 2001 (Alam, 2007). Frequent storms and occasional cyclones are a further challenges in maintaining *ghers* in this part of the exposed coast. One frustrated shrimp farmer said, "*Bagda* (shrimp) is no longer profitable. We invest huge money for the preparation of *gher, bagda* fry collection and release in the *gher,* shrimp food and labour but if the *gher* is affected by virus or by cyclone then we do not get any return from the *gher*. We fall in total loss. In the beginning of shrimp *gher*, 10–20 years ago it was so profitable but at present we are facing loss even after huge investments."

The increase of salinity, rapid alteration of the landscape ecology, frequent natural calamities, a lack of modern techniques for shrimp cultivation and shrimp diseases are some of the factors that have been responsible for why shrimp farming is not as good as it could be.

Calculated CO_2 emission in the coastal area of Bangladesh ranged from 0.35 to 0.64 kg ce/kg (see Table 7) considering the crop area, net yield, soil texture, soil type, soil organic matter, soil moisture, soil drainage, soil pH, urea, triple super phosphate (TSP), muriate of potash (MOP), cow dung and pesticide used in rice production. By comparison, in India and China it was found to range from 1.2 to 1.5 kg ce/kg and 0.72–2.74 kg ce/kg respectively, considering nitrogen fertiliser input, diesel consumption, electricity consumption for irrigation, households applying manure, households utilising no-till techniques, households practicing straw returning and households practicing straw burning (Zhang et al., 2017). In aquaculture, shrimp was found to have the largest global warming impact (Henriksson et al., 2018; Kauffman et al., 2017). As noted in Section 2, in this paper only an estimate of the emissions from aquaculture within this area could be made. Using this estimate, it was shown that hectare-wise CO_2 emissions were higher in rice compared to shrimp production, and on average the highest CO_2 was emitted from SR followed by T (see Table 7).

Table 7
GHG emissions from agricultural systems.

GHG emission	Agricultural systems								
	S		SR		R		I		T
	Rice	*Gher*	Rice	*Gher*	Rice	Pond	Rice	*Gher*	Rice
CO_2 emission (kg ce/ha)	1438	–	2552	–	3193	–	2252	–	1829
CO_2 emission (kg ce/kg)	0.64	–	0.58	–	0.61	–	0.35	–	0.64
CO_2 emission (kg ce/ha)	–	791	–	1357	–	22.27	–	1139	–
Average CO_2 emission (kg ce/ha)	1114.5		1954.5		1607.64		1695.5		1829

Note: Crop area, net yield, soil texture, soil type, soil organic matter, soil moister, soil drainage, soil pH, Urea, TSP, MOP and cow dung and pesticide were considered to calculate CO_2 emissions from rice production.

4. Conclusions

This study is an attempt to understand the energy efficiency of the various agricultural systems of coastal Bangladesh. Energy use efficiency in agriculture is crucial for the protection of the environmental quality (Fan et al., 2012) of the surrounding areas and is an important indicator of agricultural sustainability (Lorzadeh et al., 2011). In coastal Bangladesh, shrimp-based agricultural systems were found to be very energy-intensive, whereas rice-based agricultural systems or rice-prawn-and-vegetable-based agricultural systems were more energy-efficient. This study shows that energy analysis can provide a useful synthesis of information from evaluating different agricultural systems. The information is useful for sustainability assessment of agricultural systems as well as for promoting the benefits of integrated agriculture.

Agricultural systems in coastal Bangladesh depend on many physical, chemical and social factors. Salinity of water and soil is the most dominant limiting factor for agricultural production. Nevertheless, this study shows that the integrated agricultural system involving multiple crops as well as aquaculture are faring well in coastal Bangladesh. It is expected that the findings reported in this paper will be helpful for policy makers, agricultural personnel and the farmers of coastal Bangladesh. This study reveals that an integrated agricultural system is the most efficient in terms of energy use. However, a point to be noted is that the energy indicators mentioned in this paper are not the only measures of agricultural efficiency. Other indicators such as water use and economic efficiency could also be employed.

The energy aspects of agricultural systems require additional study as energy is central to all human activities and agriculture as a whole is major energy consumer as well as energy producer. In the limited number of other studies, the holistic consideration of all aspects of the energy equation is often not accounted for. In this respect, the paper makes an original contribution in two ways – as a particular case study in an agriculturally important area of the world, and as a model for studies elsewhere, forming the basis for further insights and for comparisons of diverse agricultural situations.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2018.11.030.

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