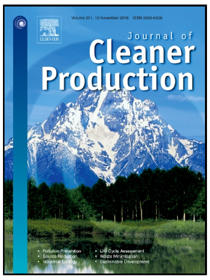

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# Accounting Emergy-based sustainability of crops production in India and Pakistan over first decade of the 21st century.

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## Abstract

Agriculture is one of the main assets of Pakistani and Indian economies, employing in both countries about 50% of the total labour force. Thus, improving agricultural sustainability in the Indo-Pak region has important implications for the local population as well as the rest of the world that relies on food imports from these countries. This article investigates the drivers and consequences of changes in crop production sustainability in India and Pakistan from an emergy-based perspective, from 2001 to 2011. However, due to the numerous crops cultivated in these regions, a detailed calculation of unit emergy values (UEVs) for each crop was not possible, therefore the paper presents a balance at country level (based on literature data for the crops' UEVs), rather than a canonical emergy accounting.

The emergy perspective was chosen to holistically evaluate and compare the environmental pressures caused by crop production in both countries. Emergy-based indicators were calculated based on the real time series of input renewable and non-renewable sources. The major findings of the work revealed that purchased renewable inputs, such as irrigating water, and purchased non-renewable inputs, such as agricultural labor, are the largest contributors among the total inputs in both countries. Labor accounted for 46.79% and 60.59% of total emergy input for crop production in India and Pakistan respectively. Overall, the production efficiency in India was greater than that in Pakistan. Emergy of crop production in Pakistan witnessed an increase of only 23%, whereas India saw an increase of 42% during the study period. Despite the lack of data on each specific agricultural process, this trend is an evidence of the fact that, if on one side the agricultural activities in the two countries were intensified to supply an increasing population, on the other side, although India performed better than Pakistan, the sustainability of the agricultural practices (from a nature-oriented perspective as assessed with emergy analysis) in both countries did not improve. . Trends of carrying capacity indicated that intensive means of agricultural production are threatening natural resources in both countries. This study empirically demonstrates the need to conserve natural resources, especially water, which have been rapidly declining in these two countries. Since both countries share these resources, this study represents an evidence for the need to cooperate for transboundary natural resource management.

## Key Words

Emergy; Sustainable development; developing country; agriculture; resource conservation; ecological accounting.

## 1. Introduction

The Indian subcontinent forms a major geographical portion of the South Asian region and it is home to more than a billion people (Ahmed et al., 2016). Politically this area has been divided into different countries of which India and Pakistan form the largest countries in both size and population (Haub and Kent, 2007). Pakistan with 201 million people is the fifth most populated country in the world while India is the second most populous country in the world with a population of 1.3 billion people and these populations are projected to increase further in the future owing to the high population growth rates in both countries (World Bank, 2010-2014). This scenario has obvious implications for food and nutritional security in these countries as 60% of all Pakistanis are food insecure, ranking 77th on the Food Security Index, with India at the 74th position (Economic Intelligence Unit, 2017). This looks surprising, given that currently both India and Pakistan are already some of the largest producers in the world of major food crops such as wheat, rice, cotton, sugarcane, etc., thus ranking among the top 10 countries in terms of agricultural output (Ray et al., 2013). Agriculture is also one of the main assets of Pakistan's economy, contributing by more than 25% to the national GDP and employing more than 50% of the labour workforce (Pakistan Bureau of Statistics, 2011). Similarly, the share of agriculture to the national GDP in India is 18.1% and this sector employs 48.8% of the total labour force (Directorate of Economics & Statistics, 2016). Hence, improving agricultural sustainability in the Indo-Pak region is primordial for the local population as well as the rest of the world that relies on food imports from these countries.

It must be noted that in both India and Pakistan, large parts of the country consist of dry, rugged and uncultivable area and the population and agricultural load centers in these countries can be traced along the rivers. Yet, due to high rates of urbanization, fertile agricultural land is being converted to housing projects thus decreasing the cultivable land (Baloch, 2011), (Pandey and Seto, 2015). Additionally, to cope with an increasing food demand, intensive means of agricultural production are taxing Pakistan's natural resources. For instance, soil erosion, salinity and water logging are persistent problems faced by the farm sector in India and Pakistan (Murgai et al., 2001). Electricity shortages and domestic natural gas consumption for urea production are additional concerns in Pakistan (Kessides, 2013). Further constraints are caused by natural disasters such as floods (Dorosh et al., 2010) and political issues such as internally displaced people (Kugelman and Hathaway, 2010).

Since when India and Pakistan gained independence from the British Raj in 1947, there have been different studies tracing the trajectory of both countries using different economic, social and political parameters (Azam and Khan, 2016; Merten, 2016). Such studies help gauge performance of these countries with respect to each other as well as international benchmarks such as the Human Development Index (Morse, 2003) and Millennium Development Goals (Hogan et al., 2010). Previous studies have been conducted to compare economic pointers (Shah et al., 2006), nutritional indicators (van den Bold et al., 2015) or productivity factors (Murgai et al., 2001). Relatively few researchers (Ali et al., 2019; Benbi and Brar, 2009; Netting, 1993) have holistically compared the environmental sustainability of agricultural systems in India and Pakistan, such as crop-production, livestock breeding, fishing, etc., on a spatial and temporal scale. These studies are mostly conducted from an end-user point of view, thus neglecting the donor- or nature-centric aspects of sustainable agriculture. Given these drawbacks and the paucity of scientific studies gauging the sustainability of crop production in South Asian countries, it is imperative to consider current and future food and water security challenges in the assessment of agricultural sustainability related to the Indian subcontinent.

This study aims at addressing some of these challenges by comparing the environmental sustainability of crops production in India and Pakistan over time. Accordingly, the analysis can disclose some of the potential loopholes and shortcomings in the current sustainability assessment practices, and help devise policies that can lead resource conservation without jeopardizing agricultural productivity at the same time. In this paper, a donor (nature-centric) perspective is considered by adopting the concept of emergy (Odum, 1996), which can be a valuable approach to identify unsustainable patters associated with economic, social and environmental flows at the large scale of a country, in particular for the assessment of crop production sustainability (Chen et al., 2006a; Siche et al., 2010).

The concept of emergy, initially developed by the American ecologist H. T. Odum in the 1980's (Odum, 1986; Odum, H., 1996) is defined as the total solar equivalent energy/exergy of one kind that was used up (directly or indirectly) in making a product or a service. Emergy can therefore aggregate energy and matter flows of different nature into a common unit, using conversion factors called unit emergy values (UEVs) (Brown and Ulgiati, 2004), which express the amount of equivalent solar energy invested in the production of a unit quantity of a delivered resource (usually measured in solar emjoules per gram (sej/g)). Larger UEVs indicate that a large quantity of equivalent solar energy went into creating the product/resource/service thus ranking it higher in the energy hierarchy in nature.

Solar energy is chosen as the common numeraire according to the rational that all forms of energy are considered to be a manifestation of solar energy (Odum, H.T., 1996). If the delivered resource is energy, the UEVs are called *transformities* (usually measured in solar emjoules per joule (sej/J)). Emergy represents therefore a way to convert all resources (including energy resources) in energy and express them in the same type of energy. According to this view, any natural and man-managed system has embodied solar energy, which can be measured on a common scale through the emergy analysis method.

## 2. Materials and methods

### *2.1 Case study*

The case study dealt with in this paper concerns emergy analysis of Indian and Pakistani crop production systems between the years 2002 and 2011, including the major output crops of these countries. The study period could not span before 2002 and after 2011 because of the lack of consistent statistical data before 2002 (for India) and beyond the year 2011 (for Pakistan). Primary data for agriculture inputs was obtained from the national statistics bureaus in India and Pakistan (Directorate of Economics & Statistics, 2016; Pakistan Bureau of Statistics, 2011). The case study includes the analysis of the renewable and non-renewable inputs required to grow major crops in Pakistan and India, as shown in Figure 1a and 1b respectively. For the present analysis we chose 12 major crops from Pakistan and 13 major crops from India based on their annual output volume. The quantitative share of the remaining crops in both countries was quite low compared to the crops considered in the present analysis. Similarly, some crop types, such as fodder crops for animal consumption, were not considered due to their relatively low emergy uptake.

[Insert Figure 1a here]

[Insert Figure 1b here]

It is important to mention here that a general national economic assessment of Pakistan and India, performed according to an emergy approach, is already existing in the NEAD database (NEAD, 2017), but it is based on the money/emergy ratio and not on a detailed emergy accounting of the agriculture system (Sweeney et al., 2009). Figure 2 provides the trend of some emergy outputs over time for Pakistan and India. The production categories shown in the graphs below include the term Agriculture which is synonymous with the term ‘crop’ used in our analysis. While these trends can be helpful for a broad overview of the economic sectors in both countries, a more dedicated analysis is required to understand the major drivers of change within these sectors and sub-sectors. Hence, in this article we aim to focus on different constituents of crop production in India and Pakistan in detail and over a greater period of time. This will help us analysing different factors behind trends and identifying needs for improvement. Differences between the results from this study and those reported in (Sweeney et al., 2009) will be examined accordingly in the Discussions section.

Our main goal in this paper is to use time series data for India and Pakistan to understand if their agricultural practices are sustainable. This analysis covers the whole countries while ignoring their myriad farming practices across different provinces, districts or towns. Since the Indian subcontinent covers a vast area with essentially different resources, climates and socio-economic conditions, there are no consistent sets of inputs or best practices for any crop variety across the length and breadth of the region. In such a situation, one could either have a series of studies covering, say, a particular crop variety in a particular district *or* cover aggregate data for the whole country. In the former case there should be a 1:1 ratio between inputs and outputs for each crop and as such one should calculate the UEVs for individual crops by aggregating the corresponding inputs. However, in view of the significant time and resources needed for a very detailed study covering the whole region, in this paper we focused on the latter approach. Hence, instead of a canonical emergy accounting study, we produce a balance of the entire country, based only on literature data for the UEVs of single crops.

[Insert Figure 2 here]

### 2.2 Short state-of-the-art on emergy analysis

Especially during the last two decades researchers have used transformities for an emergy analysis of systems ranging, just to name a few, from power production (Brown and Ulgiati, 2002), waste management (Ali, Mustafa et al., 2018), and industrial production (Zhang et al., 2009) to sustainability analysis of agriculture (La Rosa et al., 2008; Wang et al., 2017) and crop production systems (Wang, Xiaolong et al., 2014), (Jaklič et al., 2014). Emergy analysis has been used for assessing the sustainability of agricultural production in large agricultural systems such as the Chinese one. For instance, (Jiang et al., 2007) presents a system account for the Chinese agriculture in 2004. The study compares the aggregate fluxes and emergy-based indicators for the Chinese agriculture in 2004 with those for 2000, calculated in another study(Chen et al., 2006b) to illustrate the development of the Chinese agriculture in those 5 years. The study revealed that already almost 20 years ago the Chinese agriculture showed a fast decrease in sustainability due to the rapid transition from a self-supporting tradition based on intensive manure utilization and local labour force input to the modernized style of crop cultivation, with intensive consumption of industrial products.

(Tao et al., 2013) carried out an emergy evaluation of crop production for 30 provinces across China showing that a majority of the provinces could not achieve high performances on environmental and economic goals simultaneously. (Wang, Xiuhong et al., 2014) showed that the emergy sustainability index of the agricultural system in the study area (Northwest China) was relatively high compared with those of the developed regions or countries, but decreased significantly after the government implemented the grain-for-green policy, an initiative promoting ecological restoration of the ecologically vulnerable regions of the country. Similarly, (Zhang et al., 2016) carried out a temporal emergy analysis of Chinese crop production in the period between 2000 and 2010 and their results showed a reduction in the sustainability (evaluated with the "environmental sustainability index") of Chinese crop production during this period. For Brazil (Cavalett and Ortega, 2009) demonstrated that producing raw soybean and soy meal for international markets made the country lose a great amount of emergy and nutrients. Similarly, despite increased reliance on commercial energy and indirect labor for agriculture in Denmark, (Rydberg and Haden, 2006) concluded that agriculture systems could only result in limited emergy yields.

### *2.2 Methodology and indicators*

In the emergy analysis approach proposed in this paper, U represents the emergy used as a net result of emergy investment into the system by renewable (R), local nonrenewable (N), purchased nonrenewable ($F_N$) and purchased renewable ($F_R$) Emergy inputs. A number of emergy-related sustainability assessment indicators can be calculated starting from the inventory of national emergy flows (Brown et al., 2013).

In this paper, four indicators are used:

1) Unit Emergy Value (UEV) of a crop: U / $Q_i$, in sej/g, which is calculated for each individual crop *i* by dividing the total emergy of the production system of the crop by the mass output of that crop for a given year (masses of the crops are expressed in tons and converted to grams for this indicator); following this calculation, crops are considered *co-products* according to the emergy algebra rules (Odum, 1996), making the UEV a proxy measure of production efficiency to compare same crops grown in different locations;
2) Emergy Yield Ratio: EYR = U / ($F_N$ +$F_R$), which measures the contribution of a resource or process to the economy per unit of environmental loading (Ohnishi et al., 2017);
3) Environmental Loading Ratio: ELR = ($F_N$+N) / ($F_R$+R), which is a monitor of sustainability and it can be defined as ratio of nonrenewable/renewable (Ortega et al., 2002);
4) Emergy Investment Ratio, EIR = ($F_N$ + $F_R$) / (N + R), which measures the investment made by the economy in exploiting local resources (Ohnishi et al., 2017);
5) Emergy Sustainability Index, ESI = EYR / ELR, which measures the contribution of a scenario to the economy per unit of environmental stress (Ohnishi et al., 2017).

Table 1 shows the UEVs used to calculate the emergy of inputs and outputs in this study. All values have been updated according to the latest emergy baseline of 12.1E+24 seJ (Brown and Ulgiati, 2016); seJ = solar energy joules, which is the unit of measurement for emergy analysis. The outputs listed in Table 1 were chosen after a review of the national agricultural statistics in both countries which identified major crops by volume for each country (Directorate of Economics & Statistics, 2016; Pakistan Bureau of Statistics, 2011).

Table 1 - Unit Emergy Values used in this study.

| Items | Unit | Unit Emergy Value | References |
|---|---|---|---|
| **Inputs** | | | |
| **Local Renewable Sources (R)** | | | |
| **Sunlight** | sej/J | 1.00E+00 | By definition |
| **Wind** | sej/J | 1.20E+03 | (Sweeney et al., 2009) |
| **Rain - Chemical** | sej/J | 2.31E+04 | (Ghisellini et al., 2014) |
| **Earth Cycle** | sej/J | 1.54E+04 | (Sweeney et al., 2009) |
| **Local Non-Renewable Sources (N)** | | | |
| **Top Soil Loss** | sej/J | 9.40E+04 | (Ghisellini et al., 2014) |
| **Purchased Non-Renewable Sources ($F_N$)** | | | |
| **Nitrogen fertilizer** | sej/g | 4.84E+09 | (Ghisellini et al., 2014) |
| **Phosphate fertilizer** | sej/g | 4.97E+09 | (Ghisellini et al., 2014) |
| **Potash fertilizer** | sej/g | 1.40E+09 | (Ghisellini et al., 2014) |
| **Pesticides** | sej/g | 4.58E+09 | (Ghisellini et al., 2014) |
| **Diesel** | sej/g | 3.67E+09 | (Bastianoni et al., 2009) |
| **Residual furnace oil** | sej/g | 3.45E+09 | (Bastianoni et al., 2009) |
| **Machinery** | sej/g | 1.01E+10 | (Campbell et al., 2005) |
| **Electricity - Pakistan** | sej/J | 2.20E+05 | (Sweeney et al., 2009) |
| **Labor** | sej/hr | 3.09E+12 | (Ali et al., 2018) |
| **Seeds** | sej/J | 2.55E+05 | (Zhang et al., 2016) |
| **Purchased Renewable Sources ($F_R$)** | | | |
| **Irrigating Water** | sej/g | 5.77E+05 | (Ghisellini et al., 2014) |
| **Outputs (Y)** | | | |
| **Rice** | sej/g | 2.45E+09 | (González-Mejía and Ma, 2017) |
| **Wheat** | sej/J | 3.07E+05 | (Houshyar et al., 2018) |
| **Corn** | sej/g | 1.10E+10 | (González-Mejía and Ma, 2017) |
| **Beans** | sej/J | 9.10E+05 | (Brandt-Williams and Pillet, 2003) |
| **Tubers** | sej/J | 8.30E+04 | (Cheng et al., 2017) |
| **Cotton** | sej/J | 1.09E+06 | (Peng et al., 2018) |
| **Peanuts** | sej/J | 1.90E+06 | (Cheng et al., 2017) |

| | | | |
|---|---|---|---|
| **Rape seed** | sej/J | 3.31E+04 | (Takahashi and Ortega, 2010) |
| **Sugarcane** | sej/J | 3.56E+04 | (Pereira and Ortega, 2010) |
| **Beetroots** | sej/J | 1.08E+05 | (Zhang et al., 2016) |
| **Fruits** | sej/g | 6.87E+09 | (González-Mejía and Ma, 2017) |
| **Vegetables** | sej/g | 7.78E+09 | (González-Mejía and Ma, 2017) |
| **Coffee and Tea** | sej/g | 7.73E+09 | (González-Mejía and Ma, 2017) |
| **Jute** | sej/g | 1.75E+10 | (Giannetti et al., 2011) |

Since the percentage of R contained in labor and seeds is unknown, in a precautionary manner we considered them as $F_N$ instead of $F_{R,}$ as in some other studies (Zhang et al., 2016).

## 3. Results

### 3.1 Total Emergy input and its composition for Pakistan and India

Figures 3 presents the trends of emergy inputs into Pakistani and Indian crop production between 2002 and 2011. For Pakistani crop production, the average annual share of R, N, $F_R$ and $F_N$ among the inputs stood as 2.09%, 1.44%, 15.51% and 80.96% respectively during this period. It can be seen that the combined emergy of the inputs increased slightly during the study period. Moreover, even though the absolute emergy value of some of the inputs increased, the relative emergy share among the inputs decreased. Specifically, the relative share of R, N and $F_R$ among the inputs decreased by 14.31%, 14.66% and 17.81% while in absolute terms their emergy values increased by 6.22%, 5.79% and 1.88% respectively. The relative contribution of $F_N$ to the inputs increased by 4.33% and in absolute terms its emergy value increased by 29.32%. It needs to be highlighted that 2007-08 was an abnormal year, where the drop in emergy input was mainly due to reduction in the production of agricultural machinery in the country (as explained ahead).

For India, the average annual share of R, N, $F_R$ and $F_N$ among the inputs stood as 2.63%, 1.26%, 20.53% and 75.57% respectively during this period. It can be seen that the combined emergy of the inputs increased each year during the study period. Moreover, even though the absolute emergy value of some of the inputs increased, the relative emergy share among the inputs decreased. Specifically, the relative share of R and $F_R$ among the inputs increased by 1.75%and 14.23% respectively while in absolute terms their emergy values increased by 9.75% and 23.21% respectively. The relative contribution of N and $F_N$ to the inputs decreased by 6.74% and 3.49% respectively and in absolute terms their emergy values increased by 0.59% and 4.09%. The results display trends similar to that for Pakistan however the magnitude of the absolute values was much larger in case of India.

[Insert Figure 3 here]

To explore the trends in detail it is important to break down the emergy of the inputs to analyse their sub-components. Figure 4 displays the change in the relative shares of different components of $F_N$ over the studied period.

For Pakistan the constituents of the emergy values of $F_N$ include emergy values from fertilizers whose average share of $F_N$ in the study period amounted to 3.51%. This was followed by emergy contributions of electricity (1.25% avg.), mechanical equipment (65.13% avg.), fuels (0.10% avg.), pesticides (0.06% avg.), labor (27.49% avg.) and seeds (2.45% avg.) to $F_N$. During the study period, the relative emergy contribution of fuels, pesticides, labor, fuel and seeds to $F_N$ decreased by 48.73%, 9.55%, 82.24 and 18.20% respectively, while those of fertilizer, electricity and mechanical equipment increased by 3.66%, 23.72% and 4.54% respectively. Barring fuels and pesticides, absolute emergy contribution of all inputs increased during the study period. Overall, the results shown in Figure 4 point towards increasing electrification in agriculture and a decreasing trend of fuel and pesticide use for crop production. This is the result of the fact that the absolute quantities and emergy values of fuels and pesticides decreased, while those of all remaining inputs to $F_N$ increased, during the study period. Pesticides are mainly used for the cotton crop in Pakistan. The total input of pesticides for cotton production has been decreasing in the country, partly due to awareness drives led by international agencies regarding balanced use of pesticides (Khan, 2011). Similarly, electricity seems to be substituting fuels for operating equipment such as tube wells. This is a noteworthy element, given that the country has been suffering a severe power crisis since the last decade, pointing towards the fact that the contribution of electricity could have been even greater had there been a sufficient supply of electricity to the national grid. As mentioned previously, in 2007-08 there was a sudden reduction in agricultural machinery production in the country. As said above, 2007-08 was an abnormal year and it does not represent the trend, which is of a gradual but very slight reduction in the share of mechanical equipment and a gradual increase in the share of labor to $F_N$.

For India, overall, the major constituent of the emergy values of $F_N$ includes emergy value from labor whose average share of $F_N$ in the study period amounted to 79.21%. This was followed by emergy contributions of fertilizers (7.05%), electricity (5.81% avg.), fuels (2.07% avg.), seeds (5.37%), mechanical equipment (0.47% avg.) and pesticides (0.02% avg.) to $F_N$. During the study period, the relative emergy contribution of labor and seeds to $F_N$ decreased by 7.44% and 3.66% respectively, while those of fertilizers, electricity, mechanical equipment, pesticides and fuels increased by 52.38%, 48.65%, 149.45%, 13.48% and 3.29% respectively. Once again, the trends are similar to those for Pakistan except that the relative share of mechanical equipment was much less and that of labor was much more in case of India. Another difference was that the relative share of labor had been falling in case of India. Similarly, the rise in consumption of mechanical equipment, electricity and pesticides was much greater in India during the study period. The absolute emergy values of all inputs, except labor, increased during the study period in India.

[Insert Figure 4 here]

Figure 5 displays the change in the relative shares of different components of R over the studied period in India and Pakistan. In Pakistan, for R, earth cycle had the greatest percentage share of emergy input, which stood an average value of 61.56%, followed by those of wind (29.51%), sunlight (7.61%) and rain (1.26%). The relative emergy contributions of sunlight, wind and earth cycle to R decreased by 1.38%, 0.59% and 0.59% respectively. On the other hand the relative percentage contribution of rain to R increased by 62.60%. In absolute terms the emergy values of all these inputs increased during the study period.

In contrast to the results for Pakistan, overall, for R in India, wind had the greatest percentage share of emergy input which stood at an average value of 49.51%, followed by those of rain (22.46%), sunlight (18.54%) and earth cycle (9.49%). The relative emergy contributions of sunlight and wind to R decreased by 8.35% each. On the other hand the relative percentage contribution of rain and earth cycle to R increased by 22.26% and 20.91% respectively. In absolute terms the emergy values of all these inputs increased during the study period.

[Insert Figure 5 here]

During the study period, in Pakistan, the relative emergy input of N decreased by 14.66% with an average annual value of 8.95E+21 sej. In absolute terms the emergy input of N increased during the study period. Top soil loss was the only constituent of N in this study. Similarly, the relative emergy input of $F_R$ decreased by 17.81% with an average annual value of 9.64E+22 sej. In absolute terms the emergy input of $F_R$ increased during the study period. Irrigation water was the only constituent of $F_R$ in this study.

In India, the relative emergy input of N decreased by 22.13% with an average annual value of 2.25E+22 sej. In absolute terms the emergy input of N increased during the study period. Top soil loss was the only constituent of N in this study. Similarly, the relative emergy input of $F_R$ decreased by 4.62% with an average annual value of 3.66E+23 sej. In absolute terms the emergy input of $F_R$ increased during the study period. Irrigation water was the only constituent of $F_R$ in this study.

## 3.2 Total emergy output for India and Pakistan

### *3.2.1 Total emergy output and its composition for Pakistan*

Table II provides the percentage shares of emergy outputs for each crop type relative to the other crops for Pakistan considered in this analysis on an annual basis between the years 2002 and 2011. Table III provides the absolute values for emergy corresponding to each crop type across different years. As given in Tables II and III, the combined yield (Y) of the twelve crops rose by 30.15%, with an annual average emergy value of 2.71E+23 sej in this period. As for the different crop types, the largest and smallest emergy contributors to the combined emergy output of the 12 crops for Pakistan included wheat and beetroot respectively. The relative share of emergy values from wheat, tuber and maize increased, while that from all remaining crops decreased during the study period. The largest change can be seen in case of beetroot whose quantity and emergy value decreased by 94.93%, while the smallest change occurred for rice whose output quantity and emergy values decreased by 4.34%. In absolute terms, except for rapeseed, beetroot and peanuts, the emergy values and quantities of all output crops increased during the study period. This shows that the focus of farmers in Pakistan is on cash crops such as maize and wheat, whereas some calorie-rich crops such as beans (including sorghum and millet) and peanuts have received lesser attention from farmers and policy makers.

Table II- Relative annual Emergy output (%) of twelve categories of Pakistani crops between 2002 and 2011.

| **Period** | Wheat | Rice | Cotton | Sugarcane | Fruits | Vegetables | Tuber | Rapeseed | Beetroot | Beans | Peanuts | Maize |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2001-2002 | 35.14% | 4.21% | 16.36% | 2.04% | 17.93% | 9.89% | 0.27% | 0.09% | 0.06% | 3.89% | 2.04% | 8.10% |
| 2002-2003 | 35.58% | 4.67% | 15.14% | 2.13% | 16.78% | 9.53% | 0.29% | 0.09% | 0.04% | 5.87% | 1.75% | 8.13% |
| 2003-2004 | 35.46% | 4.95% | 14.61% | 2.14% | 16.31% | 9.83% | 0.28% | 0.09% | 0.04% | 5.39% | 2.18% | 8.71% |
| 2004-2005 | 33.47% | 4.37% | 17.66% | 1.61% | 16.19% | 8.43% | 0.25% | 0.07% | 0.02% | 5.76% | 1.24% | 10.93% |
| 2005-2006 | 33.40% | 4.89% | 16.34% | 1.55% | 17.68% | 8.75% | 0.20% | 0.06% | 0.01% | 3.66% | 1.13% | 12.32% |
| 2006-2007 | 35.60% | 4.67% | 15.71% | 1.84% | 14.48% | 8.56% | 0.32% | 0.07% | 0.01% | 5.66% | 1.18% | 11.91% |
| 2007-2008 | 32.49% | 4.85% | 14.45% | 2.18% | 17.54% | 8.68% | 0.32% | 0.06% | 0.01% | 3.98% | 1.35% | 14.10% |
| 2008-2009 | 34.85% | 5.67% | 13.70% | 1.60% | 16.11% | 8.32% | 0.34% | 0.06% | 0.01% | 4.89% | 1.30% | 13.15% |
| 2009-2010 | 34.98% | 5.80% | 15.49% | 1.63% | 16.42% | 8.15% | 0.38% | 0.05% | 0.01% | 3.90% | 0.84% | 12.35% |
| 2010-2011 | 37.35% | 4.02% | 13.69% | 1.81% | 16.17% | 8.28% | 0.42% | 0.06% | 0.00% | 3.31% | 1.05% | 13.86% |
| Average | 34.92% | 4.94% | 15.60% | 1.85% | 16.66% | 8.98% | 0.29% | 0.07% | 0.02% | 4.71% | 1.51% | 10.44% |
| Change | 6.29% | -4.54% | -16.31% | -11.55% | -9.82% | -16.24% | 55.82% | -33.37% | -94.93% | -15.12% | -48.42% | 71.12% |

Table III- Annual emergy output (sej) of twelve categories of Pakistani crops between 2002 and 2011.

| **Period** | Wheat | Rice | Cotton | Sugarcane | Fruits | Vegetables | Tuber | Rapeseed | Beetroot | Beans | Peanuts | Maize |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2001-02 | 7.95E+22 | 9.51E+21 | 3.70E+22 | 4.62E+21 | 4.05E+22 | 2.24E+22 | 6.04E+20 | 1.93E+20 | 1.25E+20 | 8.80E+21 | 4.61E+21 | 1.83E+22 |
| 2002-03 | 8.36E+22 | 1.10E+22 | 3.56E+22 | 5.00E+21 | 3.94E+22 | 2.24E+22 | 6.83E+20 | 2.05E+20 | 8.50E+19 | 1.38E+22 | 4.11E+21 | 1.91E+22 |
| 2003-04 | 8.50E+22 | 1.19E+22 | 3.50E+22 | 5.13E+21 | 3.91E+22 | 2.36E+22 | 6.80E+20 | 2.08E+20 | 9.87E+19 | 1.29E+22 | 5.23E+21 | 2.09E+22 |
| 2004-05 | 9.42E+22 | 1.23E+22 | 4.97E+22 | 4.54E+21 | 4.56E+22 | 2.37E+22 | 7.11E+20 | 1.89E+20 | 4.77E+19 | 1.62E+22 | 3.48E+21 | 3.08E+22 |
| 2005-06 | 9.28E+22 | 1.36E+22 | 4.54E+22 | 4.29E+21 | 4.91E+22 | 2.43E+22 | 5.50E+20 | 1.58E+20 | 3.69E+19 | 1.02E+22 | 3.15E+21 | 3.42E+22 |
| 2006-07 | 1.02E+23 | 1.33E+22 | 4.48E+22 | 5.26E+21 | 4.13E+22 | 2.44E+22 | 9.06E+20 | 1.93E+20 | 3.30E+19 | 1.62E+22 | 3.37E+21 | 3.40E+22 |
| 2007-08 | 9.14E+22 | 1.36E+22 | 4.06E+22 | 6.14E+21 | 4.93E+22 | 2.44E+22 | 8.91E+20 | 1.62E+20 | 2.53E+19 | 1.12E+22 | 3.80E+21 | 3.97E+22 |
| 2008-09 | 1.05E+23 | 1.70E+22 | 4.12E+22 | 4.81E+21 | 4.84E+22 | 2.50E+22 | 1.03E+21 | 1.74E+20 | 2.53E+19 | 1.47E+22 | 3.90E+21 | 3.95E+22 |
| 2009-10 | 1.02E+23 | 1.69E+22 | 4.50E+22 | 4.75E+21 | 4.77E+22 | 2.37E+22 | 1.10E+21 | 1.42E+20 | 2.53E+19 | 1.13E+22 | 2.43E+21 | 3.59E+22 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2010-11 | 1.10E+23 | 1.18E+22 | 4.03E+22 | 5.32E+21 | 4.76E+22 | 2.44E+22 | 1.23E+21 | 1.68E+20 | 8.25E+18 | 9.73E+21 | 3.09E+21 | 4.08E+22 |
| Avg. | 9.44E+22 | 1.31E+22 | 4.15E+22 | 4.99E+21 | 4.48E+22 | 2.38E+22 | 8.39E+20 | 1.79E+20 | 5.10E+19 | 1.25E+22 | 3.72E+21 | 3.13E+22 |
| Change (%) | 38.34% | 24.25% | 8.93% | 15.13% | 17.37% | 9.02% | 102.81% | -13.29% | -93.40% | 10.47% | -32.87% | 122.72% |

### *3.1.4 Total emergy output and its composition for India*

Table III provides the percentage shares of emergy outputs for each crop type relative to the others for India on an annual basis between the years 2002 and 2011. Table IV provides the absolute emergy values for each crop type across different years. As given in Table IV and V, emergy yield (Y) of major thirteen crops in India rose by 42.84% with an annual average value of 2.45E+24 sej in the study period. As for its composition, the largest and smallest emergy contributors to the combined emergy output of the 13 crops for India included vegetables and rapeseed respectively. The relative share of emergy from rice, wheat, sugarcane, jute, beans, peanuts, tea and coffee among the outputs decreased while the relative share of emergy from remaining crops increased during the study period. The largest change can be seen in case of cotton, whose quantity and emergy value decreased by 131.10% while the smallest change occurred for beans, whose output quantity and emergy values decreased by 4.47%. It is important to note that, except for jute, the absolute emergy values and output quantities of all crops discussed in this paper increased during the study period. These results are different from those of Pakistan, as the focus in Indian crop production seems to be on cotton, which is primarily used for textile industry. The results in both countries are similar for peanut and bean production.

Table IV- Relative annual emergy output (%) of thirteen categories of Indian crops between 2002 and 2011.

| **Period** | Wheat | Rice | Cotton | Sugarcane | Fruits | Vegetables | Tuber | Rapeseed | Jute | Beans | Tea & coffee | Maize | Peanuts |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2001-2002 | 14.93% | 10.76% | 1.64% | 1.34% | 13.90% | 23.69% | 0.40% | 0.21% | 1.48% | 9.33% | 0.42% | 6.81% | 15.08% |
| 2002-2003 | 15.61% | 9.58% | 1.64% | 1.50% | 16.91% | 26.08% | 0.44% | 0.18% | 1.67% | 8.98% | 0.47% | 6.68% | 10.24% |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2003-2004 | 14.08% | 9.71% | 2.14% | 1.01% | 14.12% | 22.73% | 0.36% | 0.25% | 1.37% | 9.89% | 0.40% | 7.38% | 16.58% |
| 2004-2005 | 13.31% | 9.06% | 2.55% | 1.01% | 15.55% | 26.86% | 0.37% | 0.30% | 1.24% | 8.66% | 0.41% | 6.94% | 13.74% |
| 2005-2006 | 12.29% | 9.15% | 2.62% | 1.10% | 15.46% | 27.68% | 0.34% | 0.29% | 1.21% | 8.07% | 0.38% | 6.58% | 14.82% |
| 2006-2007 | 13.45% | 9.31% | 3.21% | 1.39% | 16.66% | 29.39% | 0.32% | 0.26% | 1.25% | 8.57% | 0.40% | 6.76% | 9.03% |
| 2007-2008 | 12.29% | 8.50% | 3.24% | 1.20% | 16.17% | 26.18% | 0.44% | 0.18% | 1.09% | 7.85% | 0.35% | 7.48% | 15.03% |
| 2008-2009 | 12.92% | 8.92% | 2.85% | 1.01% | 17.27% | 27.05% | 0.44% | 0.23% | 1.05% | 7.93% | 0.35% | 7.97% | 12.00% |
| 2009-2010 | 13.34% | 8.27% | 3.17% | 1.06% | 18.61% | 28.63% | 0.49% | 0.22% | 1.27% | 8.23% | 0.38% | 6.97% | 9.37% |
| 2010-2011 | 12.48% | 7.75% | 3.79% | 1.08% | 16.95% | 26.72% | 0.49% | 0.24% | 0.98% | 8.91% | 0.32% | 7.87% | 12.42% |
| Average | 13.47% | 9.10% | 2.68% | 1.17% | 16.16% | 26.50% | 0.41% | 0.24% | 1.26% | 8.64% | 0.39% | 7.14% | 12.83% |
| Change | -16.42% | -28.02% | 131.10% | -19.35% | 21.91% | 12.77% | 23.90% | 12.66% | -33.75% | -4.47% | -23.08% | 15.58% | -17.65% |

Table V- Annual emergy output (sej) of thirteen categories of Indian crops between 2002 and 2011.

| **Period** | Wheat | Rice | Cotton | Sugarcane | Fruits | Vegetables | Tuber | Rapeseed | Jute | Beans | Coffeeand tea | Maize | Peanut |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2001-2002 | 3.17E+23 | 2.29E+23 | 3.48E+22 | 2.86E+22 | 2.95E+23 | 5.03E+23 | 8.40E+21 | 4.44E+21 | 3.15E+22 | 1.98E+23 | 8.93E+21 | 1.45E+23 | 3.20E+23 |
| 2002-2003 | 2.87E+23 | 1.76E+23 | 3.00E+22 | 2.76E+22 | 3.11E+23 | 4.79E+23 | 8.17E+21 | 3.39E+21 | 3.06E+22 | 1.65E+23 | 8.67E+21 | 1.07E+18 | 1.88E+23 |
| 2003-2004 | 3.15E+23 | 2.17E+23 | 4.78E+22 | 2.25E+22 | 3.16E+23 | 5.08E+23 | 8.10E+21 | 5.50E+21 | 3.05E+22 | 2.21E+23 | 8.89E+21 | 1.43E+18 | 3.71E+23 |
| 2004-2005 | 2.99E+23 | 2.04E+23 | 5.72E+22 | 2.28E+22 | 3.49E+23 | 6.04E+23 | 8.30E+21 | 6.64E+21 | 2.80E+22 | 1.95E+23 | 9.14E+21 | 1.35E+18 | 3.09E+23 |
| 2005-2006 | 3.02E+23 | 2.25E+23 | 6.44E+22 | 2.70E+22 | 3.80E+23 | 6.81E+23 | 8.39E+21 | 7.11E+21 | 2.97E+22 | 1.98E+23 | 9.45E+21 | 1.41E+18 | 3.64E+23 |
| 2006-2007 | 3.30E+23 | 2.29E+23 | 7.88E+22 | 3.42E+22 | 4.09E+23 | 7.22E+23 | 7.79E+21 | 6.50E+21 | 3.07E+22 | 2.11E+23 | 9.75E+21 | 1.44E+18 | 2.22E+23 |
| 2007-2008 | 3.43E+23 | 2.37E+23 | 9.02E+22 | 3.35E+22 | 4.51E+23 | 7.30E+23 | 1.22E+22 | 5.10E+21 | 3.04E+22 | 2.19E+23 | 9.65E+21 | 1.81E+18 | 4.19E+23 |
| 2008-2009 | 3.52E+23 | 2.43E+23 | 7.76E+22 | 2.74E+22 | 4.70E+23 | 7.37E+23 | 1.21E+22 | 6.29E+21 | 2.87E+22 | 2.16E+23 | 9.55E+21 | 1.88E+18 | 3.27E+23 |
| 2009-2010 | 3.52E+23 | 2.18E+23 | 8.37E+22 | 2.81E+22 | 4.91E+23 | 7.56E+23 | 1.28E+22 | 5.77E+21 | 3.34E+22 | 2.17E+23 | 9.90E+21 | 1.60E+18 | 2.48E+23 |
| 2010-2011 | 3.79E+23 | 2.35E+23 | 1.15E+23 | 3.29E+22 | 5.14E+23 | 8.11E+23 | 1.49E+22 | 7.15E+21 | 2.98E+22 | 2.70E+23 | 9.81E+21 | 2.08E+18 | 3.77E+23 |
| Average | 3.28E+23 | 2.21E+23 | 6.80E+22 | 2.85E+22 | 3.99E+23 | 6.53E+23 | 1.01E+22 | 5.79E+21 | 3.03E+22 | 2.11E+23 | 9.37E+21 | 1.45E+22 | 3.14E+23 |
| Change | 19.39% | 2.82% | 230.10% | 15.20% | 74.13% | 61.08% | 76.97% | 60.92% | -5.37% | 36.45% | 9.87% | -100.00% | 17.62% |

### 3.3 Emergy based indicators

Figure 6 shows the change in UEVs for both India and Pakistan in the period between 2002 and 2011. The figure shows UEVs to have increased by 5.69% for Pakistan with an average annual value of 3.48E+09 sej/g. For India UEV increased by 10.65% with an average annual value of 2.80E+09 sej/g. It is important to note the fluctuations in UEVs for both countries, indicating that there has not been a permanent change in such values in the studied period.

[Insert Figure 6 here]

Figure 7 shows the change in EYR, ELR, EIR and ESI for Pakistani and Indian crop production between 2002 and 2011. It can be seen that EYR for Pakistan decreased by 13.43% with an annual average value of 0.46. On the other hand, EYR for India increased by 32.37% with an annual average value of 1.43. ELR for Pakistani crop production increased by 25.91% with an annual average value of 4.99. On the other hand, ELR for India decreased by 14.43% with an average value of 3.32. Moreover, EIR for Pakistan increased by 17.53% with an annual average value of 28.87. On the other hand, EIR for India increased by 1.18% with an average value of 24.7. Similarly, ESI for Pakistan decreased by 31.24 % with an annual average value of 0.11. ESI for India increased by 54.70% with an average value of 0.43.

[Insert Figure 7 here]

## 4. Discussion

### 4.1 Main Findings

Emergy indicators show that the trends for both India and Pakistan point towards an increasing load on the environment for crop production. Overall sustainability of crop production, from an emergy perspective, is worse in the case of Pakistan. Lack of improvements will result in worsening of emergy indicators for both countries. Increasing populations in both countries have already reduced the biologically productive land available per person. This can also be seen in Figure 8. The calculations used to generate the graph are provided in the Appendix.

[Insert Figure 8 here]

On average, output to input emergy ratio for Pakistan during the study period stood at 43.40% which was significantly less than that for India (91.62%). As shown in Figure 9 during the study period, this ratio increased by 5.00% and 10.58% for Pakistan and India respectively. For every square meter of cultivated land, emergy of crop production in Pakistan has witnessed an increase of only 23.03%, whereas India has witnessed an increase of 42.00% during the study period. The main driver for this change in India was output of cotton which increased more than five times between 2002 and 2011, whereas crop-production for remaining crops, except peanuts, also increased. In case of Pakistan, production of rapeseed, beetroot, beans and peanuts decreased while of the remaining crops tuber showed the largest increase of 68.13%.

[Insert Figure 9 here]

Of all the inputs, absolute quantities and emergy contributions from mechanical equipment have experienced the greatest increases for both countries, rising by 128.15% and 159.65% for Pakistan and India respectively. This is because agricultural mechanization is on the rise in both countries. This has also led to an increase in electricity consumption in both countries, which raised by 60.00% and 54.74% in Pakistan and India respectively. Here the difference is that in case of Pakistan this increase in electricity consumption has been matched by a decrease in fuel consumption in both absolute and relative terms. Further investigation is needed to explore the reasons behind this trend.

## 4.2 Comparison with other studies

In some cases, Pakistani and Indian crop-production system seem to have better emergy indicators as compared to other large neighboring Asian countries such as China for which such nationwide studies exist in the literature. For instance, while UEV for Pakistan and India had an average value of 2.80E+09 sej/g and 3.48E+09 sej/g between 2002 and 2011, that for China had a value of 1.24E+09 sej/g between 2000 and 2010 when adjusted according to the new emergy baseline (Brown and Ulgiati, 2016). In case of some other indicators, the situation was opposite. For instance, ESI for China in 2010 stood at 0.80 (Zhang et al., 2016) while that for Pakistan and India in the same year was 0.07 and 0.48 respectively., Our results did not vary to a significant degree compared to the findings reported by (Sweeney et al., 2009). For instance for 2004 and 2008 we calculated the emergy of crop production in India as 2.23E+24 sej and 2.79E+24 sej respectively, while those reported by (Sweeney et al., 2009) were 7.66E+23 sej and 9.78E+23 sej for 2004 and 2008 respectively, after updating them according to the new emergy baseline (Brown et al., 2016). Similarly, the emergy of crop production in Pakistan for 2004 and 2008 in our analysis resulted in 2.40E+23 sej and 2.81E+23 sej respectively, while the values reported by (Sweeney et al., 2009) for 2004 and 2008 were 1.27E+23 sej and 1.42E+23 sej respectively after updating them according to the new emergy baseline (Brown and Ulgiati, 2016). The difference is probably due to the fact that we used government statistics for data acquisition, whereas (Sweeney et al., 2009) considered data from Food and Agriculture Organization.

### 4.3 Policy implications

Results show that the main emergy inputs in both countries were labor and irrigating water. On average, irrigating water accounted for 15.51% and 20.53% of total emergy input for crop production in Pakistan and India respectively. Currently, food exports make Pakistan the top ground water exporter in the world while India ranks third (Murtugudde, 2017). It must be noted here that at present 90% of the fresh water in Pakistan is used for irrigation, yet the annual per capita availability of water in Pakistan is among the lowest in Asia, estimated at about 1500 m$^3$ and experts estimate the country to become water scarce between 2020 and 2035 (Altaf et al., 2009), (Mekonnen and Hoekstra, 2016). Similarly, gross per capita water availability in India will decline from 1820 $m^3$/yr in 2001 to as low as 1140 $m^3$/yr in 2050 (Gupta and Deshpande, 2004). This points towards the need for conservation and technological improvements in irrigation techniques. Moreover, both countries should encourage foreign direct investment so that it can increase the productivity in their farm sector. China intends to invest in Pakistani agriculture to achieve the goal of food security for the burgeoning middle class in both countries. It identifies lack of cold storages and other infrastructure as stifling sustainability in Pakistani agriculture (DAWN, 2017). Significant improvements can be made by using renewable energy sources such as solar panels and modern farming techniques such as greenhouses (Esen and Yuksel, 2013).

On average, labor accounted for 21.60% and 59.87% of total emergy input for crop production in Pakistan and India respectively. Labor for crop production in Pakistan increased by almost 6 million workers or 16.98% between 2000 and 2011, while in India it decreased by more than 29 million people or 3.65%. Consequently, the emergy input from labor in Pakistan increased, while that in India decreased during the study period. In India, this decline has caused labor shortage in agriculture, which has had negative consequences for labor intensive crops such as paddy, wheat, cotton, sugarcane and groundnut (FICCI, 2015). Some of the reasons behind this shortage include financial reasons such as farmer bankruptcy and indebtedness, while others include changing weather patterns causing yields to fall. These factors have led to serious social issues as 16,000 farmers commit suicide each year in India due to financial problems (Merriott, 2016). This makes sustainability and efficiency the most important factors to foster for crop production in this region. Apart from technical improvements, agriculture in both India and Pakistan needs proper branding, packaging and marketing efforts so as to increase exports and achieve greater recognition in international markets. Similarly, legal issues related to land division, tenure and taxation also need to be improved so that small farmers and landholders can compete with bigger players effectively.

Similarly, fertilizer consumption has witnessed an increase in both countries due to availability of domestic natural gas for local urea production (Fiaz Hussain and Hussain, 2014; Parikh et al., 2009). However, pesticide consumption has reduced in case of Pakistan which, as explained previously, was due to a reduction in farmers' wasteful practices. The results for N show that India has done a better job of halting soil erosion as top soil loss increased only by 0.59% in India as compared to 5.79% in Pakistan between 2002 and 2011. Indian government attributed topsoil loss to high amount of fertilizer use and to control it launched National Project on Management of Soil Health and Fertility in 2008 which emphasized a more balanced use of fertilizers (Ministry of Agriculture, 2008). The absence of such a project in Pakistan is unfortunate. To resolve this, educational programs aimed at increasing the farmers' knowledge, skills and awareness regarding agricultural sustainability need to be put in place. This can help them understanding their stake in efforts needed for conservation of the local ecosystem services and natural capital for crop production (Ali, M. et al., 2018).

## 5. Conclusions

In this study, we followed the evolution of emergy of crops cultivation over time across India and Pakistan in the period 2002-2011. The main findings of this study are similar to those discovered by researchers for crop production in some other countries (Zhang et al., 2016), as well as between the two countries considered in this study. For instance, for crop production in both India and Pakistan, purchased renewable input make the largest contribution to the total input, followed by purchased non-renewable inputs, then local renewable inputs and finally local nonrenewable inputs in that order. In both India and Pakistan, the relative contributions of R and N and $F_R$ decreased while those of $F_N$ increased during the study period. However, the magnitude of reduction in relative emergy contributions from R and N was much greater in case of India.

A limitation of this study lays in the fact that we used aggregate statistics for the whole country instead of using data for a specific crop in a specific province or district. As such, this cannot be considered a canonical emergy accounting study, but rather an average emergy balance. This way of operating was forced by the existence of very different agricultural practices across different locations, which would require a huge data collection effort, unfeasible within the scope of a single paper. Another limitation is that we only considered the crop-production systems and ignored livestock, poultry and fisheries sectors. For the emergy analysis, we ignored the role of services due to lack of availability of necessary information. Most of the data was extracted from government publications, thus there can be some variation between results reported in our findings and those relying on other sources of data. Finally, since crop production can be affected by natural events or adverse weather conditions, this might cause some results to deviate from trend lines as in case of Pakistan during the period 2007-08 shown above.

The purpose of the present study was to provide a donor-based (i.e. nature-centered) evaluation of crop production sustainability in India and Pakistan. This study is also intended to provide an assessment that can be used by future studies as a benchmark using similar techniques. Future studies can also look at individual provinces or districts to gain a better understanding of resource use patterns for crop production across South Asia. This can help make comparisons with neighboring countries such as China where such detailed studies have already been carried out. Detailed comparisons can also be made for specific types of crops or farming systems across both countries, as well as those practiced in developed countries. This can help in identifying shortcomings and lead to better benchmarks and standards. Future studies can cover specific crop varieties in different districts of the Indian subcontinent using canonical emergy accounting procedures. This will help understand shortcomings and help optimize the use of resources for best practices in such locations.

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## 7. Appendix

### 7.1 Calculation of Bio-capacity

TABLE A.1 – Calculation of bio-capacity for Indian crop production system.

| Population | R/capita | global emergy density (GED) (seJ/ha)* | Bio-capacity (ha/person) |
|---|---|---|---|
| 1.09E+09 | 1.06E+14 | 2.35E+14 | 4.53E-01 |
| 1.11E+09 | 1.10E+14 | 2.35E+14 | 4.69E-01 |
| 1.13E+09 | 1.12E+14 | 2.35E+14 | 4.75E-01 |
| 1.14E+09 | 1.14E+14 | 2.35E+14 | 4.86E-01 |
| 1.16E+09 | 1.29E+14 | 2.35E+14 | 5.47E-01 |
| 1.18E+09 | 1.17E+14 | 2.35E+14 | 4.96E-01 |
| 1.20E+09 | 1.14E+14 | 2.35E+14 | 4.84E-01 |
| 1.21E+09 | 1.03E+14 | 2.35E+14 | 4.39E-01 |
| 1.23E+09 | 1.17E+14 | 2.35E+14 | 4.99E-01 |
| 1.25E+09 | 1.15E+14 | 2.35E+14 | 4.90E-01 |

*From (Bai et al., 2015) updated according to the latest emergy baseline of 12.1E+24 (Brown and Ulgiati, 2016)(Brown et al., 2016).

TABLE A.2 – Calculation of bio-capacity for Pakistani crop production system.

| Population | R/capita | global emergy density (GED) (seJ/ha)* | Bio-capacity (ha/person) |
|---|---|---|---|
| 1.45E+08 | 9.30E+13 | 2.35E+14 | 3.96E-01 |
| 1.48E+08 | 8.91E+13 | 2.35E+14 | 3.79E-01 |
| 1.51E+08 | 9.75E+13 | 2.35E+14 | 4.15E-01 |
| 1.54E+08 | 9.09E+13 | 2.35E+14 | 3.87E-01 |
| 1.57E+08 | 9.26E+13 | 2.35E+14 | 3.94E-01 |
| 1.60E+08 | 9.34E+13 | 2.35E+14 | 3.97E-01 |

| | | | |
|---|---|---|---|
| 1.64E+08 | 9.20E+13 | 2.35E+14 | 3.92E-01 |
| 1.67E+08 | 9.12E+13 | 2.35E+14 | 3.88E-01 |
| 1.71E+08 | 8.65E+13 | 2.35E+14 | 3.68E-01 |
| 1.71E+08 | 8.80E+13 | 2.35E+14 | 3.75E-01 |

*From (Bai et al., 2015) updated according to the latest emergy baseline of 1.12E+24 (Brown and Ulgiati, 2016).

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## Figure Captions

Figure 1a. Annual crop output for 12 major crop types in Pakistan.

Figure 1b. Annual crop output for 13 major crop types in India.

Figure 2. Annual trend of agricultural output for India and Pakistan.

Figure 3. Emergy by type for inputs in Pakistani and Indian crop production between 2002 and 2011.

Figure 4. Relative share of subcomponents of $F_N$ in Pakistani and Indian crop production between 2002 and 2011.

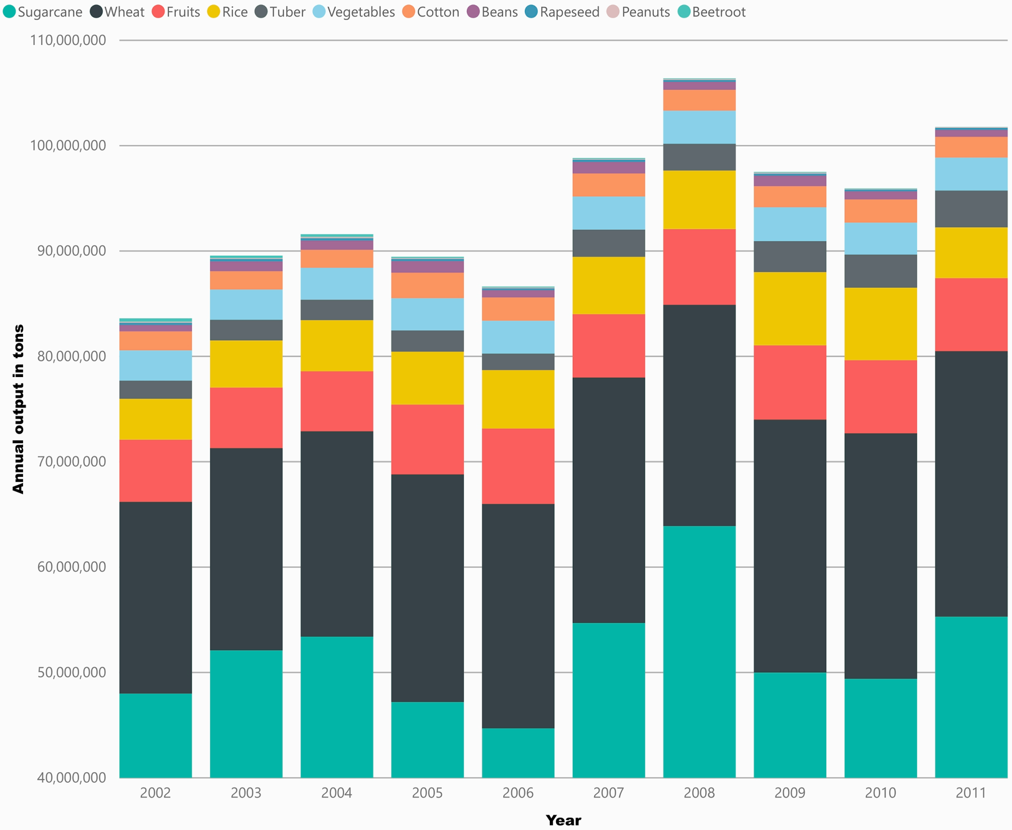
Figure 5. Relative share of subcomponents of R in Pakistani and Indian crop production between 2002 and 2011.

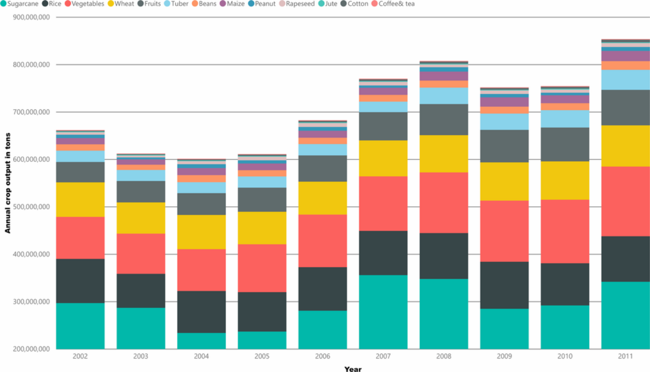
Figure 6. Trends of UEV in Pakistani and Indian crop production between 2002 and 2011.

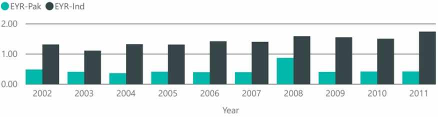
Figure 7. Trends of emergy ratios in Pakistani and Indian crop production between 2002 and 2011.

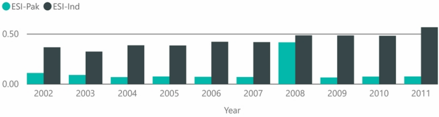
Figure 8. Trends of carrying capacity in Pakistani and Indian crop production between 2002 and 2011.

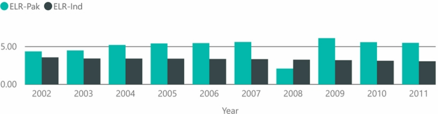
Figure 9. Trends of the ratio between output emergy and input emergy in Pakistani and Indian crop production between 2002 and 2010. Since the study considered major inputs and outputs only, the ratios differ from 100%.

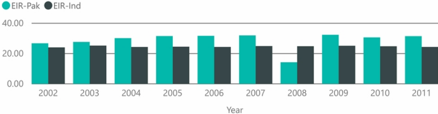

Sugarcane
Wheat
Fruits
Rice
Tuber
Vegetables
Cotton
Beans
Rapeseed
Peanuts
Beetroot
110,000,000
100,000,000
90,000,000
80,000,000
70,000,000
60,000,000
50,000,000
40,000,000
Annual output in tons
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Year

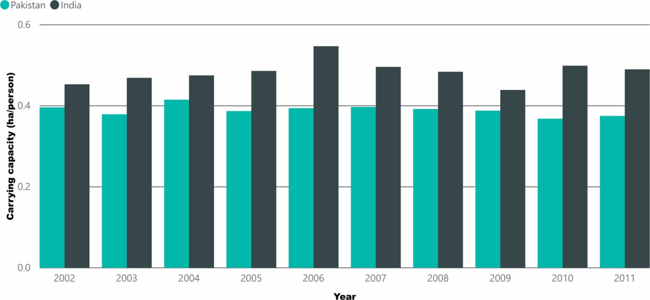

Sugarcane
Rice
Vegetables
Wheat
Fruits
Tuber
Beans
Maize
Peanut
Rapeseed
Jute
Cotton
Coffee& tea
900,000,000
800,000,000
700,000,000
600,000,000
500,000,000
400,000,000
300,000,000
200,000,000
Annual crop output in tons
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Year

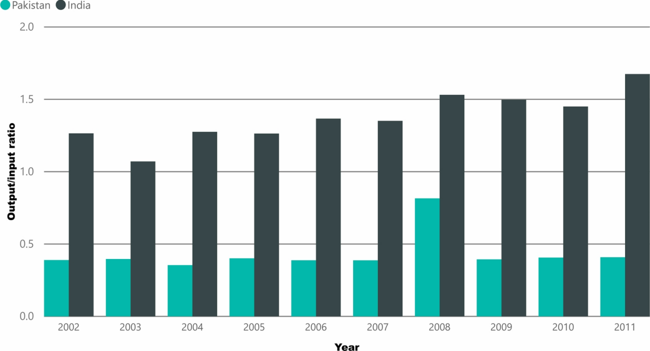

Emergy Yield Ratio


Emergy Sustainability Index

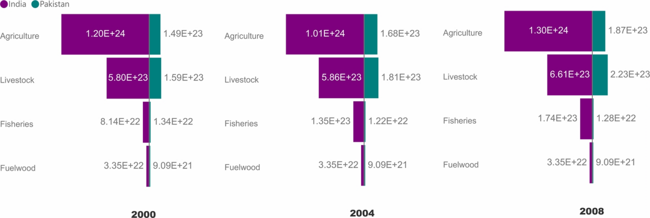

Emergy Loading Ratio


Emergy Investment Ratio


● Pakistan
● India
0.6
0.4
0.2
0.0
Carrying capacity (ha/person)
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Year



Pakistan
India
2.0
1.5
1.0
0.5
0.0
Output/input ratio
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Year



India
Pakistan
Agriculture
1.20E+24
1.49E+23
Livestock
5.80E+23
1.59E+23
Fisheries
8.14E+22
1.34E+22
Fuelwood
3.35E+22
9.09E+21
2000
Agriculture
1.01E+24
1.68E+23
Livestock
5.86E+23
1.81E+23
Fisheries
1.35E+23
1.22E+22
Fuelwood
3.35E+22
9.09E+21
2004
Agriculture
1.30E+24
1.87E+23
Livestock
6.61E+23
2.23E+23
Fisheries
1.74E+23
1.28E+22
Fuelwood
3.35E+22
9.09E+21
2008


R
2011
4.87E+22
1.32E+22
2010
4.82E+22
1.34E+22
2009
4.68E+22
1.36E+22
2008
4.77E+22
1.34E+22
2007
4.76E+22
1.33E+22
2006
4.83E+22
1.30E+22
2005
4.70E+22
1.28E+22
2004
4.65E+22
1.29E+22
2003
4.41E+22
1.23E+22
2002
4.44E+22
1.24E+22
N
2011
2.28E+22
9.04E+21
2010
2.24E+22
9.22E+21
2009
2.28E+22
9.32E+21
2008
2.27E+22
9.21E+21
2007
2.25E+22
9.10E+21
2006
2.27E+22
8.94E+21
2005
2.26E+22
8.80E+21
2004
2.27E+22
8.86E+21
2003
2.12E+22
8.44E+21
2002
2.27E+22
8.55E+21
India
Pakistan
FN
2011
1.34E+24
6.00E+23
2010
1.36E+24
5.97E+23
2009
1.36E+24
6.46E+23
2008
1.37E+24
2.24E+23
2007
1.38E+24
6.16E+23
2006
1.36E+24
5.97E+23
2005
1.35E+24
5.84E+23
2004
1.33E+24
5.59E+23
2003
1.31E+24
4.76E+23
2002
1.29E+24
4.64E+23
FR
2011
3.97E+23
9.76E+22
2010
3.93E+23
9.52E+22
2009
3.86E+23
9.36E+22
2008
3.78E+23
9.82E+22
2007
3.71E+23
9.81E+22
2006
3.64E+23
9.78E+22
2005
3.57E+23
9.66E+22
2004
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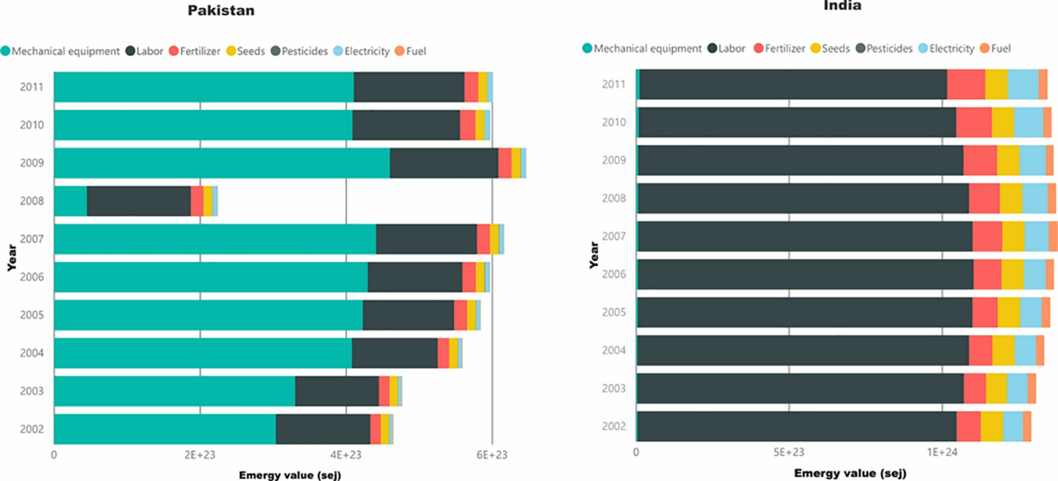
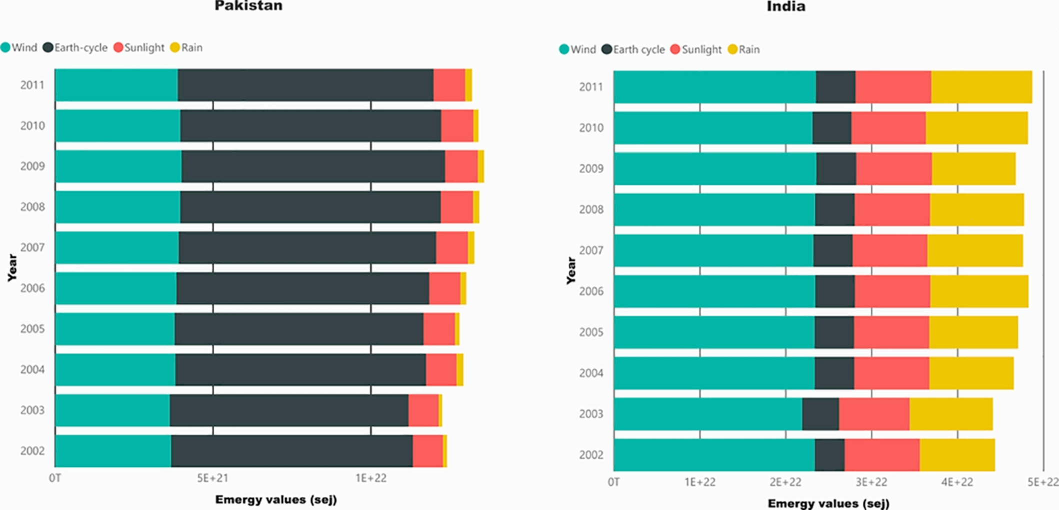
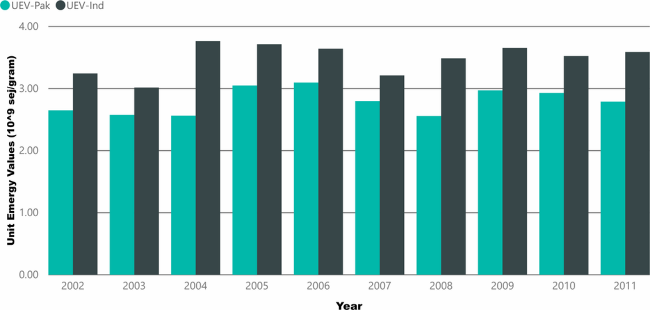
9.59E+22
2003
3.43E+23
9.57E+22
2002
3.22E+23
9.58E+22


Pakistan
India
Mechanical equipment
Labor
Fertilizer
Seeds
Pesticides
Electricity
Fuel
Year
2011
2010
2009
2008
2007
2006
2005
2004
2003
2002
0
2E+23
4E+23
6E+23
5E+23
1E+24
Emergy value (sej)


Pakistan
Wind
Earth-cycle
Sunlight
Rain
Year
2011
2010
2009
2008
2007
2006
2005
2004
2003
2002
0T
5E+21
1E+22
Emergy values (sej)
India
Wind
Earth cycle
Sunlight
Rain
Year
2011
2010
2009
2008
2007
2006
2005
2004
2003
2002
0T
1E+22
2E+22
3E+22
4E+22
5E+22
Emergy values (sej)


● UEV-Pak
● UEV-Ind
Unit Emergy Values (10^9 sej/gram)
4.00
3.00
2.00
1.00
0.00
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Year