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Eco-efficiency of cotton-cropping systems in Pakistan: an integrated approach of life cycle assessment and data envelopment analysis

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ABSTRACT

This study investigates the balance between economic and environmental performances of cotton cropping systems in Southern Punjab, Pakistan. Eco-efficiency analysis was performed using Data Envelopment Analysis to integrate economic and environmental performances, which were assessed through life cycle assessment. All 169 cotton cropping systems were individually analyzed. Special attention was paid to farm size as a possible factor of performances variation. The results show that pesticides and fertilizer use, field emissions, field operations and irrigation are the main sources of environmental impacts. It reveals that production of 1 kg of seed cotton delivered at farm gate generates a global warming potential of 3–3.4 kg CO_{2e} and requires 5–6 L of water. Eco-efficiency estimates of small, medium and large sized farms computed on per hectare basis are 0.86, 0.74 and 0.78, respectively, and 0.51, 0.52 and 0.50 respectively when computed on the basis of kilogram of seed cotton. No significant differences of eco-efficiencies per functional unit were observed across farm size categories. Small farms' higher profits counterbalance their significantly higher levels of eutrophication, and balance its overall eco-efficiency with other farm categories. A trade-off analysis tried to identify the farms that would epitomize sustainable cotton production; it shows that it is almost impossible to combine high economic return with low environmental impacts under current context. However some recommendations have been formulated with regards to pesticides and fertilizers use, which may be significantly reduced with no effect on yield, and potentially reduce environmental impacts.

1. Introduction

Cotton contributes substantially to the national economy of Pakistan and is a key source of livelihood for the rural poor (Pakistan Economic Survey, 2013–2014). It is mainly cultivated under irrigated conditions with a high pest hazard as certain insects are particularly harmful to yields and fibre quality. Cotton production requires huge amounts of resources such as water, fossil energy and agro-chemicals, whose utilization degrades the environment in different ways (Shafiq and Rehman, 2000). The excessive use of fertilizers contributes greenhouse gas emissions and water pollution (IPCC, 2006). In Pakistan, freshwater resources are being contaminated through runoff and leaching of nitrates from agricultural land (Azizullah et al., 2011) and overuse and misuse of chemical pesticides (Tariq et al., 2007). Mechanization has also increased the use of non-renewable energy. The magnitude of these environmental impacts and resource use in different forms varies depending upon the farm management practices, soil properties, and agro-ecosystem conditions (Choudhury and Kennedy, 2005). Also, intensive input use, as a form of insurance for cotton yield and quality, comes with high production costs. Both environmental damages and high costs of cotton production challenge its sustainability and farmers' income in Pakistan; therefore analysing and quantifying jointly environmental impacts and economic performances of cotton production is necessary. The question remains as to how environmental impacts can be reduced while farmer income is sustained. The issue underlying in this research is the trade-off between input use, environmental impact and economic performance in cotton cropping systems of Pakistan.

LCA is a widely used methodology to assess environmental performances of products and processes taking into account the whole life cycle of the products (ISO 14040, 2006; ISO 14044, 2006).

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It helps to identify the environmental impacts hotspots and corresponding decisions can be defined (Baumann and Tillman, 2004). There are limitations to use LCA as a stand-alone methodological approach to sustainability analysis (Vázquez-Rowe et al., 2012). To that aim economic-ecological efficiency or commonly known as eco-efficiency is a useful operational concept. The concept of eco-efficiency refers to a process' increase output value, and lesser negative impacts (World Business Council for Sustainable Development, 2000). Eco-efficiency was defined by OECD. (1998) as the ratio of economic value per environmental impacts. Indicators related to eco-efficiency can be assessed through a product's economic value against its environmental impact (Kuosmanen and Kortelainen, 2005; Van Passel, 2007). Eco-efficiency can help policy-makers to formulate, implement and assess measures to improve the economic activity with reduced amount of negative impacts on environment. Van Passel et al. (2007) stated that eco-efficiency is a useful operational metric to assess farm level sustainability. It may be used as a proxy to sustainability indicator (OECD, 1998). Picazo-Tadeo et al. (2012) argued that any given production process leads to a set of environmental impact indicators (e.g. through the use of life cycle assessment -LCA), hence to a set of eco-efficiency ratios.

Based on the common definition of eco-efficiency, Thanawong et al. (2014) have assessed the eco-efficiency of rice cropping systems in Thailand. The approach provides a reasonable proxy to sustainability analysis, yet it faces the issue of multiple eco-efficiency ratios or indicators (as many as the environmental impact indicators). Interpreting so many indicators may prove cumbersome and, above all, impractical. Therefore integrating both economic and environmental information into a single eco-efficiency indicator may help interpret and compare cases.

Data Envelopment Analysis (DEA) has recently been introduced as a tool to compute such single eco-efficiency score (Kuosmanen and Kortelainen, 2005). Traditionally DEA has been used in industry to evaluate the relative efficiency of decision making units (DMUs) based on commercial inputs and outputs, which is known as technical efficiency (Korhonen and Luptacik, 2004). DEA has only recently been used in agricultural case studies with the pioneering works by De Koeijer et al. (2002) and Reig-Martínez and Picazo-Tadeo (2004). With the advancement of DEA approach, researchers have started handling the environmentally undesirable outputs into their models as a by-product (e.g. Zhang et al., 2008; Picazo-Tadeo et al., 2011; Avadí et al., 2014), leading to eco-efficiency. Low eco-efficiency score of any given production system always results from low income and/or high environmental impacts. The joint application of LCA and DEA (e.g. Vázquez-Rowe et al., 2012; Mohammadi et al., 2013) has recently emerged as a way to find out trade-off options between environmental impacts and economic return. This approach also helps to compute the potential reduction of environmental impacts through possible reduction of inputs, towards higher eco-efficiency.

This research combines LCA with DEA as an attempt to compute eco-efficiency indicators in a set of cotton cropping systems in Pakistan. To the authors' knowledge, no comprehensive LCA research on cotton has been done in South Asia, let alone research on cotton cropping systems' eco-efficiency. The environmental impacts of a global cotton textile chain have been studied by Steinberger et al. (2009) with LCA, but a single, average production situation was considered, regardless of local diversity.

The objective of our research was to study the sustainability of diverse cotton cropping systems in the Punjab province of Pakistan. The potential influence of farm size as a factor to sustainability was also investigated. Potential environmental impacts were modelled through LCA methodology. Economic performances were assessed, and eco-efficiency scores were computed with DEA.

2. Materials and methods

2.1. Sampling and data collection strategy

Analyses were performed on primary data collected from sampled cotton farming systems of Lodhran and Vehari districts of Southern Punjab, Pakistan, the most suitable area for cotton cultivation (Ali and Abdulai, 2010). Irrigation requirements of cotton are partially fulfilled by surface water and partially by groundwater. Land preparation activities for cotton cultivation are performed mechanically but sowing and cultural management practices (weeding, fertilizing and pesticide spray) are performed either manually or mechanically depending upon farmers' decisions and resources availability. But entire picking of cotton is performed manually. The data were collected using field surveys and structured questionnaire at the farm level. Two hundred cotton farms were selected and surveyed in the two districts. Sampling was done on stratified random basis, in order to select farms of different sizes, which included small (<5 ha) 40 farms, medium (5–20 ha) 68 farms and large (>20 ha) 61 farms. Such classification refers to the land-holding classification of the State Bank of Pakistan. Also, we tried to select systems with different intensification and mechanization levels, as existing in Southern Punjab. Some questionnaires were discarded because of missing data or incoherent information, and 169 cropping systems were eventually used for analyses. Data collection mainly encompassed the consumption of all production factors (inputs per ha) that were used during the cropping season of 2010. In addition, the yields in seed cotton (seed and lint, i.e., un-ginned picked cotton) and the market value of all inputs and the seed cotton were recorded. Gross income, total cost incurred during cotton production, and the value added (net income) were computed for each studied system and used for eco-efficiency estimation.

The Mann–Whitney U-test (two-sided) was used wherever necessary, to determine whether farm size categories possessed significantly different features.

2.2. Environmental impact analysis with LCA

2.2.1. System boundary and specification

Cradle-to-farm-gate approach was used to evaluate the potential environmental impacts of cotton farming systems. The functional unit used refers to the mass of seed cotton produced, delivered at farm gate. The unit used (kg or metric ton) depended upon convenience and adequacy in displaying the results. In this study the potential environmental impacts were computed as per kilogram of seed cotton i.e. seed and lint together. Fig. 1 shows the flow diagram of the studied cotton cropping systems.

2.2.2. Life cycle inventory analysis

Life cycle inventory (LCI) was done with the help of primary data collected through field survey (e.g. input use). Each field operation and input was documented for each system in terms of its type or composition (active ingredients), weight or dose, use time, use schedule, market price and application costs, and fuel consumption as shown in Table 1. Water consumption, both green water (from rainfall and soil stock) and blue water (from irrigation) were modelled based upon the concepts of crop evaporative demand, soil–water relationships, and irrigation system losses. The modelling platform CROPWAT (FAO, 1992), version 8 was used.

2.2.3. Direct field emissions

The direct emissions to air were modelled based on the methods developed by Intergovernmental Panel on Climate Change (IPCC, 2006). Fertilizer-induced emissions were calculated based upon