Ecological Indicators 62 (2016) 117–137

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Emergy and end-point impact assessment of agricultural and food production in the United States: A supply chain-linked Ecologically-based Life Cycle Assessment

Yong Shin Park[a], Gokhan Egilmez[b,*], Murat Kucukvar[c]

[a] Upper Great Plains Transportation Institute, North Dakota State University, Fargo, ND 58108, United States
[b] Department of Mechanical and Industrial Engineering, University of New Haven, West Haven, CT 06512, United States
[c] Department of Industrial Engineering, Istanbul Sehir University, Istanbul 34662, Turkey

ARTICLE INFO

Article history:
Received 6 April 2015
Received in revised form
17 November 2015
Accepted 19 November 2015

Keywords:
Ecologically-based Life Cycle Assessment
Mid-point
End point impacts
Eco-efficiency
Nonrenewable resource
Renewable resource
Agri-food industry

ABSTRACT

The concept of tracing the ecologically-based life cycle impacts of agricultural and food industries (AFIs) has become a topic of interest worldwide due to their critical association with the climate change, water and land footprint, and food security. In this study, an in-depth analysis of ecological resource consumption, atmospheric emissions, land and water footprints of 54 agricultural and food industries in the U.S. were examined extensively. Initially, the supply-chain linked ecological life cycle assessment was performed with Ecologically-based Life Cycle Assessment (Eco-LCA) tool. Then, the results of life cycle inventory were used to assess the mid and end-point impacts by using the ReCiPe approach. Thirdly, ecological performance assessment was performed using well-known metrics, including loading and renewability ratios and eco-efficiency analysis. As a novel comprehensive approach, the integrated framework that consists of the Eco-LCA, ReCiPe and linear programming-based ecological performance assessment is of importance to have an overall understanding about the extent of impacts related to agricultural and food production activities across the U.S. Results indicated that grain farming, dairy food, and animal production-related sectors were found to have the greatest shares in both environmental and ecological impact categories as well as endpoint impacts on human health, ecosystem and resources. In terms of climate change, animal (except poultry) slaughtering, rendering, and processing (ASRP), cattle ranching and farming (CRF), fertilizer manufacturing (FM), grain farming (GF), fluid milk and butter manufacturing (FMBM) were found to be the top five dominant industries in climate change impacts accounting for about 60% share of the total impact.

1. Introduction

1.1. Sustainable agriculture and food production

Agriculture and food industries (AFIs) are integral elements of today's economies for sustaining supply chains and final consumption. While providing the very basic needs to people; during the agricultural and production activities of food, various environmental issues arise such as land, water and energy use, and atmospheric emissions (Notarnicola et al., 2012; Kucukvar and Samadi, 2015). In the U.S., agriculture and food industries are the main driver sectors of the national economy, which account for 15% of total household consumption and $775.8 billion to the national gross domestic product (GDP) (USDA, 2012). While providing substantial economic benefits to the country, AFIs are accounted for 10% of total U.S. greenhouse gas (GHG) emissions in 2012, which has risen by 17% since 1970 due to high increase of nitrous oxide (N_2O) and methane emissions that were resulted from increased use of agricultural machinery (Mohammadi et al., 2013). Additionally, AFIs' impacts are notable in land and water footprint categories. For instance, significant portion of the land use in the U.S. (accounting for 1.2 billion acres) and approximately 40% of water withdrawals are attributed to such activities as irrigation, sanitization, etc. in AFIs. While the socio economic benefits are indispensable, federal and state organizations (e.g., USDA NIFA's sustainable agriculture programs) have recently been allocating significant amount of resources to increase environmental sustainability performance of AFI industries in terms of energy, water and land use impact categories (Egilmez et al., 2014).

* Corresponding author. Tel.: +1 2034974196.
E-mail address: gokhan.egilmez@ndsu.edu (G. Egilmez).

http://dx.doi.org/10.1016/j.ecolind.2015.11.045
1470-160X/

1.2. Scope of policy making

Over the decades, substantial efforts toward stabilizing the rising emissions trend and minimizing resource consumption rates by increasing efficiency of agricultural and machinery activities have greatly improved environmental performance of AFIs (Parry et al., 2007; Beddington and Asaduzzaman, 2012; USDA, 2012). In this regard, Food, Conservation, and Energy Act in 2008 has established the Agriculture and Food Research Initiative (AFRI) to address the critical policy focus areas such as mitigating and adapting to climate change, ecosystem health, food security, etc. (Jordan and Warner, 2010), in addition to the U.S. Environmental Protection Agency's (US EPA) continuing efforts toward developing analytical and practical methods related to ecosystem service from agriculture, energy sector, etc. (US EPA, 2012). While establishing policy focus areas, it is critical to quantify the environmental performance of such holistic systems. In fact, several environmental sustainability performance metrics (e.g., eco-efficiency, energy intensity, carbon intensity) have been addressed in the literature and organizational reports (US EPA, 2012; Maxime et al., 2006). The majority of the works contributed significantly in terms of environmental impact metrics such as CO_2-equivalent, water, energy use, toxic release and hazardous waste generation. However, very few studies extend scope of analysis toward the end point impacts with a broader ecological resource extent perspective. In this regard, accounting for the role of ecosystem goods and services such as the biogeochemical cycles, pollination, carbon sequestration, climate regulation, etc. is of importance to increase the scope of analysis that will provide a more comprehensive viewpoint for the researchers and policy makers (Jordan and Warner, 2010). Thus, decision makers can easily supported by LCA tool for formulating the judgment toward policy making and measuring environmental performance of production and supply chain practice (Ardente et al., 2003).

1.3. Life cycle assessment and agricultural and food production systems

Agri-food production is becoming the most attractive sector to many policy makers due to the fact that Agri-food production sectors dominantly contribute to environmental impact (e.g., resource depletion, land degradation, emission, and waste generation) (Beccali et al., 2009). This issue has been stressed in various studies (Gordon et al., 2010; Notarnicola et al., 2012; Marsden, 2012; Egilmez et al., 2014; Soussana, 2014). In this regard, life cycle assessment (LCA) is vastly used tool for the evaluating environmental load of process and products from cradle to grave that assess the life cycle of individual product during the specific process (Kucukvar et al., 2015). This includes all phases of product from extraction of raw material through production, distribution, consumption, and product disposal (Ardente et al., 2010; Ozawa-Meida et al., 2013; Onat et al., 2014a). Predominantly, LCA methodology has been applied to various kinds of industrial products and processes (Roy et al., 2009). One of the major strengths of this approach is that LCA is comprehensive approach as well as it can avoid of problem shifting between impacts (Finnveden et al., 2009), and it also allows easier managemnt of complex information (Ardente et al., 2010). Since there is a growing concern about sustainable agricultural product and food production, life cycle assessment can be of great help for identifying other alternatives to improve the environmental aspect of agricultural and food product at various life cycle stages to support decision makers in both private and public sectors (Arvanitoyannis, 2014).

Application of LCA on environmental management and sustainability has grown in recent years that the number of published papers has steadily increased in terms of methodology and case study based work (Notarnicola et al., 2012). LCA application on agricultural and food product, and industrial product have been identified as common environmental issues such as GHG emissions, energy use, which have been widely studied and reported on (Curran, 1996; ISO 14040, 2006; Notarnicola et al., 2012). The environmental indicator categories have addressed most frequently in AFI related LCA included energy use, global warming, eutrophication, ozone formation, acidification, and land use. Otherwise, less often studied impacts, included water use, toxicity impact, biodiversity, and erosion, etc. (Notarnicola et al., 2012). Among the various LCA tools, process-based LCA (P-LCA), economic input–output LCA (EIO-LCA), were found to be major life cycle assessment model related to environmental assessment of agricultural product and food (Kucukvar and Samadi, 2015). P-LCA is conventional method which captures the environmental impact of a product within the specific process (Park et al., 2015), which also has been used as a solid way for quantifying environmental impact. Relevant studies include industrial food product such as bread (Andersson et al., 1994; Braschkat et al., 2004; Rosing and Nielsen, 2004), fresh and canned food (Lozano et al., 2009) and mussel cultivation (Iribarren et al., 2010); dairy and meat production such as milk (Eide, 2002; Iribarren et al., 2011), cheese (Berlin, 2002; Middelaar and Berentsen, 2011; Kim et al., 2013), animal production (Pelletier et al., 2010; Nunez et al., 2005; Williams et al., 2006), and agricultural products such as rice (Blengini and Busto, 2009; Hokazono and Hayashi, 2012), sugar beet (Foteinis et al., 2011; Salazar-Ordóñez, 2013), fruit (Foster et al., 2014; Khoshnevisan and Rafiee, 2014), vegetable (Romero-Gámez, 2014), crop production in Italy (Cellura et al., 2012a,b). However, the application of P-LCA provides some limited scope of analysis without considering supply chain impacts. As system boundary becomes broader, the analysis result of the P-LCA becomes more complicated in that some of environmental impact in production chain can be overlooked (Egilmez et al., 2013). The past studies on the direct and upstream environmental footprint analysis of food manufacturing sectors also showed that the P-LCA suffers from significant truncation errors which can be order of 50% or higher (Egilmez et al., 2014; Lenzen, 2000; Wood et al., 2006). To overcome this limitation of P-LCA, environmentally extended economic input–output based LCA (EIO-LCA) was introduced in early 2000s (Hendrickson et al., 2006; Egilmez et al., 2013; Virtanen and Kurppa, 2011; Cellura et al., 2011, 2012; Egilmez and Park, 2015). The EIO-LCA extends the system boundaries by including the environmental impact of direct and indirect impact together, where the top-down LCA approach is utilized in combination with entire input–output table and environmental impact multiplier (Hendrickson et al., 2006; Kucukvar et al., 2014a; Onat et al., 2014b). A recent application of the EIO-LCA to Finnish food chain reveals key results such as having 68% of agriculture-related impacts caused by domestic production, 14% of the contribution of Agri-food industries to the total climate change impact (Virtanen and Kurppa, 2011).

In addition to the environmental and economic impact assessment with input output modeling, understanding of ecological resource consumption aspects of Agri-food products is quite limited, but is important from a sustainability perspective (Baral et al., 2012). Some different approaches have been proposed to account for ecosystem goods and services in a production system with a practice of P-LCA and integrated approach with EIO-LCA (Jeswani and Azapagic, 2010). Although effort has been made to address and quantify the implications of ecosystem goods and services on human well-being, such efforts are progressing very slowly (Daily and Polasky, 2009). Thus, humanity is facing an enormous challenge in managing ecosystem goods and services to secure adequate Agri-food production without compromising the ecological life systems on which human society has also relied (Gordon et al., 2010). Even though the scientific