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Towards a more holistic sustainability assessment framework for agro-bioenergy systems — A review

Oludunsin Arodudu [a,b,*], Katharina Helming [a,d], Hubert Wiggering [a,b], Alexey Voinov [c]

[a] *Leibniz-Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, 15374 Müncheberg, Germany*
[b] *Potsdam University, Institute of Earth and Environmental Sciences, Karl-Liebknecht-Straße 24-25, 14476 Potsdam, Golm, Germany*
[c] *ITC, Faculty of Geoinformation and Earth Observation, University of Twente, Hengelosestraat 99, Enschede, The Netherlands*
[d] *Faculty of Landscape Management and Nature Conservation, University for Sustainable Development (HNEE), Schickler Strasse 5, 16225 Eberswalde, Germany*

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ABSTRACT

The use of life cycle assessment (LCA) as a sustainability assessment tool for agro-bioenergy system usually has an industrial agriculture bias. Furthermore, LCA generally has often been criticized for being a decision maker tool which may not consider decision takers perceptions. They are lacking in spatial and temporal depth, and unable to assess sufficiently some environmental impact categories such as biodiversity, land use etc. and most economic and social impact categories, e.g. food security, water security, energy security. This study explored tools, methodologies and frameworks that can be deployed individually, as well as in combination with each other for bridging these methodological gaps in application to agro-bioenergy systems. Integrating agronomic options, e.g. alternative farm power, tillage, seed sowing options, fertilizer, pesticide, irrigation into the boundaries of LCAs for agro-bioenergy systems will not only provide an alternative agro-ecological perspective to previous LCAs, but will also lead to the derivation of indicators for assessment of some social and economic impact categories. Deploying life cycle thinking approaches such as energy return on energy invested-EROEI, human appropriation of net primary production-HANPP, net greenhouse gas or carbon balance-NCB, water footprint individually and in combination with each other will also lead to further derivation of indicators suitable for assessing relevant environmental, social and economic impact categories. Also, applying spatio-temporal simulation models has a potential for improving the spatial and temporal depths of LCA analysis.

Contents

1. Introduction

Bioenergy has gained prominence amongst many policy stakeholders in the face of pressing energy security challenges, as well as in search for safer and more renewable energy sources for meeting global climate change mitigation and emission reduction targets (Fischer and

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* Corresponding author at: Leibniz-Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, 15374 Müncheberg, Germany.
E-mail address: Oludunsin.Arodudu@zalf.de (O. Arodudu).

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Schrattenholzer, 2001; Berndes et al., 2003; Fischer et al., 2010). However, despite its high ratings amongst decision makers, there are still many arguments, both for and against the proliferation of bioenergy infrastructures and services (Mol, 2007; UNFCCC, 2008; Arodudu et al., 2013). Several findings claim that bioenergy is one of the most effective means for reduction of global crude oil dependencies, and turning back climate change and global warming trends, through the replacement of fossil fuels and the reduction of greenhouse gas emissions (Dincer, 1999; Bertil et al., 2004; Arodudu et al., 2013). Conversely, some other findings show that bioenergy will compete indiscriminately with other important biomass supply chains including food, animal feed, industrial raw materials (Groom et al., 2008; Searchinger et al., 2008), and put further pressure on ecosystem services (Wiens et al., 2011; Koizumi, 2013). Some also claim that bioenergy will contribute to the greenhouse gas emission levels through discharges from indirect fossil energy investments across the bioenergy production chain, e.g. in production of synthetic fertilizers, pesticides, lime (Pimentel, 2003; Hill et al., 2006; van Duren et al., 2015). Current uncertainties and diversities of opinions generate debates that require holistic sustainability assessments, in order to find pathways that will orientate policy making regarding bioenergy production towards sustainability (Ness et al., 2007; Helming et al., 2011).

With respect to agriculture based bioenergy (agro-bioenergy) specifically, its sustainability has often been brought into question by its overall high energy requirements, low net energy gain and efficiency, positive net greenhouse gas emission status, and the high water footprint associated with production across the value chains (Groom et al., 2008; Searchinger et al., 2008; Gerbens-Leenes et al., 2009). Even though this is true within the contexts previously considered, most studies that have come to these conclusions assume bioenergy production to be fossil fuel dependent, energy intensive, commercially focused and essentially a product of industrial agriculture settings. Industrialized agriculture system, which is widespread in most parts of the US and Europe, favours big farm holds and large expanses of land (Patzek, 2004; Pimentel et al., 2009). It also supports the pushing of the boundaries of agricultural production for profit by whatever means possible (Hall et al., 2011; Murphy et al., 2011) even at the expense of the degradation of the environment. Examples include precision irrigation-sprinkler irrigation, drip irrigation etc., increased synthetic fertilizer and pesticide application, use of improved seeds-hybrid cultivars, genetically modified cultivars, deployment of heavy machineries and more rigorous tillage techniques (Altieri et al., 2012; Altieri et al., 2015).

An alternative to the industrial agriculture that is not usually considered within most sustainability assessments for agro-bioenergy system is the ecological agriculture or the agro-ecological production (Chappell and LaValle, 2009; Blesh and Wolf, 2014). It is widespread in Cuba, Chile and most parts of the Latin America (Wittman, 2009; Aerni, 2011). Ecological agriculture advocates degrowth and decarbonization principles such as small scale production on small fragmented land holdings that are owned by rural communities and cooperatives. This prevents local community holders from becoming landless. It is also characterized by shorter transport distances (usually less than 20 km), deployment of smaller tractor implementations (single axle tractors) or human or farm animal (e.g. ox, buffalo, horses, donkeys, mules, camels etc.) labour (Smith, 2009; Wezel et al., 2009). Agro-ecological systems also encourages management using conservation practices and principles such as reduced or no tillage operations, use of mostly native seeds, as well as less energy intensive and more organic fertilizers, limes and pesticides sourced from agricultural waste sources (e.g. manure, biogas digestates etc.) (Altieri et al., 2012; Altieri et al., 2015).

In this study, we reviewed and suggested methodologies that could be adapted within local and regional sustainability assessment framework for assessing agro-bioenergy system from an agro-ecological point of view. This is expected to provide more balanced perspective of the sustainability of agro-bioenergy systems.

However, aside the need for an agro-ecological perspective within sustainability assessment frameworks for agro-bioenergy systems, assessment methodologies usually do not answer all the questions needed for more accurate decision making. In order to bridge this methodological gap, this study first suggested methodological improvements to some of the previously used tools and methods, before discussing those specifically related to sustainability assessment of agro-bioenergy systems from an agro-ecological point of view. Section 2 reviewed the structure of what a holistic sustainability assessment framework should look like and listed impact categories relevant for agro-bioenergy systems. Section 3 and its subsections reviewed how life cycle assessment (LCA) fits into the mould of a holistic sustainability assessment framework; identified its currents weaknesses as a holistic sustainability assessment framework; and suggested improvements that can assist in bridging the methodological weaknesses identified. While Sections 3.1.1 and 3.1.2 focused on methodological improvements that are applicable to agro-bioenergy systems both from an industrial agriculture and agro-ecological point of view, Section 3.1.2 focused on methodologies for assessing agro-bioenergy systems from an agro-ecological point of view only.

2. Sustainability assessment framework for assessing agro-bioenergy systems

Since sustainability assessment is a process that aims at directing management and policy making towards sustainability, it requires answering specific what- (impacts), where- (space), when- (time) and who- (stakeholders) questions (Ness et al., 2007).

Depending on the level of detail required, the sustainability questions requiring answers could be further divided into local, regional and global for the space dimension of the sustainability assessment with local factors being part of regional and global processes or global factors influencing a system at regional or local scales (Voinov, 2008; McLellan et al., 2014; Nyerges et al., 2014). Time dimension of sustainability assessment can be divided into short, mid and long term for the time element of the sustainability assessment (Filar et al., 2009; Handoh & Handoh and Hidaka, 2010). Stakeholder dimension of the sustainability assessment can be split into decision maker and decision taker sub-divisions (Lahdelma et al., 2000; Mendoza and Martins, 2006). The impact dimension of the sustainability assessment can be delineated into environmental, social and economic impacts (Morris et al., 2011; den Herder et al., 2012). This is illustrated in Fig. 1 (Arodudu et al., 2017).

Defining and measuring sustainability by answering these questions require the use of appropriate indicators that are systemic with respect to the different impact categories concerned, sensitive to the impacts of policy or activity examined over space and time, and reflective of different stakeholder group points of view (Helming et al., 2011). We have identified from literatures a cross section of impact categories that are relevant to agro-bioenergy systems, across the three major sustainability impact divisions namely environmental, social and economic impacts (Fig. 2).

3. Extending LCA for sustainability assessment of agro-bioenergy systems

Life-cycle assessment typifies the group of tools that account for the flow of inputs and outputs of energies and materials accompanying all the different stages of a product's life (EPA, 2006; Firrisa et al., 2014). Even though LCA studies have general standards like the ISO 14040:2006 and ISO 14044:2006 (ISO, 2006a; ISO, 2006b), which practitioners often refer to as a guide, each LCA still has its own unique boundaries and settings reflecting the goals or questions in focus (Weidema, 2009; Wolf et al., 2012). The life cycle of agro-bioenergy system is from raw material extraction (plant cultivation and harvesting inclusive) through material processing, manufacture, distribution, use,