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Life Cycle Assessment of China's agroecosystems

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ABSTRACT

Agricultural Life Cycle Assessment (ALCA) is an important tool able to inform environmental improvement in agricultural ecosystems. However, many studies address only one or a few environmental aspects, and where several indicators are used, the optional steps of normalization and weighting are rarely used to support interpretation. In this study, the winter wheat-summer maize rotation, widely practiced on the North China Plain, was evaluated using a variety of indicators addressing natural resource use, human and ecosystem health. The results after normalization and weighting highlight the need to address eutrophication potential and aquatic ecotoxicity potential as significant environmental aspects, especially in the higher input winter wheat part of the rotation. Different results were obtained using Chinese normalization factors compared to global factors, highlighting the need to use local factors when local environmental challenges are the priority. With the scarcity of arable land in China, there have been concerted and successful attempts to raise yields. However, there is now a need to improve nutrient management and pest control as strategic priorities. The life cycle perspective is important because opportunities also exist to achieve environmental improvement in the local manufacturing systems for farming inputs.

1. Introduction

Life Cycle Assessment (LCA) is a technique to evaluate the potential environmental impacts of a product or service. LCA takes a holistic approach, quantifying the various forms of resource use and emissions to air, soil, and water that occur during the different stages of production, use and disposal. Although initially applied to industrial products, LCA has also been applied to agricultural systems since the 1990s (Anderson et al., 1994; Kramer et al., 1999; Brentrup et al., 2001, 2004a,b). Since this time, LCA has become established as an important technique for integrated environmental assessment of agroecosystems, with case study applications in many countries (Heller and Gregory, 2003; Rebitzer et al., 2004; Hertwich, 2005; Roy et al., 2009; Knudsen et al., 2010; Bala et al., 2010; Guinée et al., 2011; Earles and Halog, 2011; Čuček et al., 2012; Liang et al., 2013; Wang et al., 2014, 2015a–c; Notarnicola et al., 2017).

LCA has been used in China since the late 1990s, initially in the automobile and construction industries (Wang, 1999), and soon after in the agricultural sector (Yang and Nielsen, 2001; Yang et al., 2003). In particular, Agricultural Life Cycle Assessment (ALCA) has been used to understand the potential environmental risks of agricultural intensification and the development of modern agricultural production systems in China. ALCA studies have been undertaken for most of the major agricultural production systems, including wheat, maize, soybeans, vegetables, and fruits (e.g. Wang et al., 2006; Liang et al., 2009; Knudsen et al., 2010; Li et al., 2010; Liu et al., 2010a,b; Cheng et al., 2011; Xia and Yan, 2011; Lu et al., 2012; Huang et al., 2013; Wang et al., 2014, 2015b, 2017a; Hu et al., 2016). Other studies have assessed bioethanol and biomass production systems (e.g. Hu et al., 2004, 2008; Leng et al., 2008; Ou et al., 2009; Yu and Tao, 2009; Yan and Crookes, 2009; Yang et al., 2009; Hou et al., 2011; Kan et al., 2015; Yi et al., 2015; Zhao et al., 2016; Zhang et al., 2017b). ALCA studies have also

Abbreviations: AEP, aquatic ecotoxity potential; ALCA, Agricultural Life Cycle Assessment; AP, acidification potential; EC, energy consumption; EP, eutrophication potential; FU, functional unit; GWP, global warming potential; HTP, human toxicity potential; HW, hazardous waste; LCA, Life Cycle Assessment; LU, land use; NCP, North China Plain; NR, nonrenewable resource; OLD, ozone layer depletion; PCS, photochemical smog; RR, renewable resource; SD, soot and dust; SW, solid waste; TEP, terrestrial ecotoxity potential; WU, water use

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extended to cover livestock production (e.g. Cao et al., 2011; Liang et al., 2013; Meng et al., 2014; Chen et al., 2015; Wei, 2016; Yao et al., 2017), as well as the processing of agricultural commodities (e.g. Corbiere-Nicollier et al., 2001; Lu and Zhang, 2010; Zhou et al., 2010; Gu and Chen, 2015; Wang et al., 2015a). Some aspect specific studies have used ALCA to investigate the impacts of pesticide (Wang et al., 2005) and fertilizer use (Zhang et al., 2013, 2017a,c; Yang et al., 2015; Wang et al., 2017b).

However, it has been common for ALCA studies to focus on only a single environmental aspect or a narrow selection of environmental aspects, such as energy and water consumption, global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP) (Berger and Finkbeiner, 2010; Cheng et al., 2011; Gu and Chen, 2015; Huang et al., 2013; Hu et al., 2016; Kan et al., 2015; Liu et al., 2010a,b; Zhang et al., 2013). Very often, the rationale for the selection of specific environmental indicators and not others has been unclear. Some environmental aspects have been rarely included in ALCA studies, including human toxicity potential (HTP), aquatic ecotoxicity potential (AET) and terrestrial ecotoxicity potential (TEP). In fact, the potential ecotoxicity caused by heavy metal inputs and pesticide use in agroecosystems has become a major issue of concern in recent years (Feng et al., 2003; Yang, 2013; Zhang, 2013; Kong, 2014; Schmidt Rivera et al., 2017; Yang et al., 2017).

Furthermore, according to the ISO standards governing LCA practice (ISO, 2006a,b), there are four phases in an LCA study – Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation of results – of which LCIA involves selection of impact categories, classification of LCI results, and application of characterization models. Normalization and weighting are additional optional steps that can facilitate interpretation of a profile of different indicator results. Agricultural production systems have a broad and diffuse interface with the natural environment that make impact assessment modelling more complex than for many types of industrial production, and ongoing method development has been necessary (Brentrup et al., 2004a,b; Canals et al., 2007; Crawford, 2008; Earles and Halog, 2011; Heijungs et al., 2007; Huijbregts et al., 2000; Corrado et al., 2018; Notarnicola et al., 2017). Few ALCA studies in China have included a broad range of environmental impact categories and used normalization and weighting steps to evaluate the significance of the different indicator results (Liang et al., 2009; Wang et al., 2015b,c).

The aim of this paper was to improve the ALCA framework in China by extending the range of relevant environmental indicators. Through application of normalization and weighting procedures, the objective was to identify critical environmental impacts in China's agroecosystems. The framework was applied to a wheat-maize rotation system in Luancheng, a typical high-yielding agricultural county in the North China Plain (NCP). The framework was also used to compare conventional production in Luancheng with selected agricultural production systems in Europe and USA.

2. Materials and method

2.1. The study area

The NCP, 320,000 km^2 in area, is China's most important region of agricultural production and home to more than 200 million people. Luancheng county (37°53′N, 114°41′E) is a typical agricultural county in the NCP, located in the western part of the plain (Fig. 1). The county covers an area of 346 km^2, and has a population of around 0.33 million people, including 0.25 million in rural communities. It has an average annual temperature of about 15 °C and about 187 frost-free days. Most of the 461 mm of average annual rain falls during the humid summer months. The Quaternary-age aquifer system underlying the county consists of laterally discontinuous layers of alluvium and reworked loess. Winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) double-cropping is the prevalent cropping system. A system of returning crop residues to the soil has been widely practiced since ~1990. Data relating to inputs and outputs per ha of winter wheat-summer maize production are presented in Table 1. These data, collected by the Circular Agriculture Research Center, China Agricultural University (Liang et al. 2009), represent the average across 2004–2006 for conventional agricultural production in Luancheng county.

2.2. LCA methodology

The LCA involved the compilation and evaluation of inputs, outputs and the potential environmental impacts of the production system throughout its life cycle, as defined by ISO (2006a,b), following the four phases described above. The objective was to identify.

2.2.1. Goals and scope

For this study, one Mg of winter wheat and summer maize grains were selected as the basis for analysis, also known as the functional unit (FU). The objective was to identify the most important environmental impacts associated with intensive cropping on the NCP, using Luancheng county in Hebei Province as the representative case. A cradle to farm gate system boundary was therefore used as downstream grain processing and use are independent of the agricultural production system. The study included raw material extraction, processing and transportation, production of agricultural inputs and their transportation, as well as farm processes (Fig. 2). For the purpose of analysis, processes were grouped as off-farm and on-farm.

2.2.2. Life cycle inventory (LCI) analysis

The LCI included both nonrenewable and renewable resource use. Nonrenewable resources primarily consist of fossil fuels and minerals. It is common for ALCA studies to concentrate on fossil fuel use due to limited availability of other data (Wang, et al., 2006, 2014, 2015a–c; Liang et al., 2013). However, agricultural machinery and irrigation equipment are an important part of intensive agricultural production in China, and the resource use and associated with their production was excluded in this study due to the lack of related data. Regarding renewable resources, both arable land and irrigation water use were included due to their central importance to agriculture and scarcity within China.

Regarding the off-farm subsystem, LCI data concerning electricity, fuel, fertilizer and pesticide production was obtained from literature (Hu et al., 2004, 2008; Wang et al., 2006; Di et al., 2007; Liang et al., 2009). Regarding the on-farm subsystem, emissions from the application of fertilizers were based primarily on field experiments conducted on the NCP. For winter wheat and summer maize, NH_3 volatilization represented 23 and 26% of N inputs and NO_3^- leaching represented 14 and 16% of N inputs, respectively (Lu et al., 2006; Liang, et al., 2009). The coefficient of direct N-loss as N_2O from inorganic and organic fertilizer by nitrification and denitrification was 1% (IPCC, 2007), and that of the indirect N-loss was 1% and 2.5% of the NH_3-N and NO_3-N released into the atmosphere and water, respectively (Brentrup et al., 2001, 2004a, b). The coefficient of P-loss was 1% of the total input for both organic and inorganic fertilizers (Lu et al., 2006; Cheng et al., 2011). Heavy metals (i.e. Cu, Cd, Zn, Pb) in irrigation water, fertilizers and grains were taken from Feng et al. (2003) and Xiao et al. (2004). For pesticides, the proportion released into the atmosphere, water and soil were 10%, 1% and 43% of the active ingredients used (Van Calker et al., 2004). The analysis was based on all crop residues being returned to the land.

2.2.3. Life cycle impact assessment (LCIA)

For LCIA a profile of 10 indicators was chosen covering renewable and nonrenewable resource use as well as emissions impacting human and ecosystem health (Table 2). The methodology used to perform characterization, normalization and weighting follows.