Journal of Cleaner Production, Vol. 172, 20 January 2018, pp. 3770-3780
DOI:10.1016/j.jclepro.2017.06.175

# Development of Crop.LCA, an adaptable screening life cycle assessment tool for agricultural systems: a Canadian scenario assessment

Pietro Goglio[a], Ward N. Smith[b], Devon E. Worth[b], Brian B. Grant[b], Raymond L. Desjardins[b], Wen Chen[b], Mario Tenuta[c], Brian G. McConkey[d], Adrian Williams[a], Paul Burgess[a]

*[a]School of Water, Energy and Environment, Cranfield University, College Road, BEDFORD, MK43 0AL, UK; [b]Ottawa Research and Development Centre, Agriculture and Agri-Food Canada, K.W. Neatby Building, Ottawa, Ontario, Canada K1A 0C6; [c]Canada Research Chair in Applied Soil Ecology, Department of Soil Science, University of Manitoba, 309 Ellis Building, 13 Freedman Crescent Winnipeg, Manitoba, Canada R3T 2N2; [d]Swift Current Research Station, Swift Current, Saskatchewan, Canada S0E 1A0*

***Corresponding author:**

Pietro Goglio, PhD

*School of Water, Energy and Environment, Cranfield University, Bedford, MK4 30AL, UK*

Phone: 0044 (0) 1234 750111 ext. 3221

Fax: +44 (0)1234 752971

E-mail: pietro.goglio@cranfield.ac.uk, pietro.goglio@gmail.com

Published by Elsevier. This is the Author Accepted Manuscript issued with:
Creative Commons Attribution Non-Commercial No Derivatives License (CC:BY:NC:ND 4.0).
The final published version (version of record) is available online at DOI:10.1016/j.jclepro.2017.06.175.
Please refer to any applicable publisher terms of use.

## Abstract

There is an increasing demand for sustainable agricultural production as part of the transition towards a globally sustainable economy. To quantify impacts of agricultural systems on the environment, life cycle assessment (LCA) is ideal because of its holistic approach. Many tools have been developed to conduct LCAs in agriculture, but they are not publicly available, not open-source, and have a limited scope. Here, a new adaptable open-source tool (Crop.LCA) for carrying out LCA of cropping systems is presented and tested in an evaluation study with a scenario assessment of 4 cropping systems using an agroecosystem model (DNDC) to predict soil GHG emissions. The functional units used are hectares (ha) of land and gigajoules (GJ) of harvested energy output, and 4 impact categories were evaluated: cumulative energy demand (CED), 100-year global warming potential (GWP), eutrophication and acidification potential. DNDC was used to simulate 28 years of cropping system dynamics, and the results were used as input in Crop.LCA. Data were aggregated for each 4-year rotation and statistically analysed. Introduction of legumes into the cropping system reduced CED by 6%, GWP by 23%, and acidification by 19% per ha. These results highlight the ability of Crop.LCA to capture cropping system characteristics in LCA, and the tool constitutes a step forward in increasing the accuracy of LCA of cropping systems as required for bio-economy system assessments. Furthermore, the tool is open-source, highly transparent and has the necessary flexibility to assess agricultural systems.



**Keywords:** LCA, cropping systems, tool, scenario assessment, agriculture, open-source

# 1. Introduction

Agriculture is responsible for feeding a growing world population, while concerns about environmental impacts rise. Worldwide, there is a need to develop bio-based economies or “bio-economies” with reduced fossil fuel use and greenhouse gas (GHG) emissions (Philp, 2015; World Bank, 2015). These bio-economies need to be sustainably managed to reduce environmental impacts, while increasing productivity and profitability (Huisingh et al., 2015; Pülzl et al., 2014). It is therefore important to quantify the impacts and synergies of agricultural systems on ecosystem services and the environment (Bosch et al., 2015; Goglio et al., 2014). The variability in pedo-climate conditions, management practices, cultivars, etc. is considerable and affects the environmental impacts of cropping systems (Nemecek et al., 2014).

With its holistic approach, life cycle assessment (LCA) has been used in many research studies to evaluate environmental impacts in agricultural production systems (Biswas et al., 2008; Nemecek et al., 2015). A variety of impact categories have been included in agricultural LCA: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), cumulative energy demand (CED), toxicity potential, and impacts on biodiversity (Goglio et al., 2012; Huijbregts et al., 2010; Kim et al., 2009; Nemecek et al., 2015).

In cropping systems, it has been observed that the impact of a crop is significantly affected by the previous crop in the cropping system (Hokazono and Hayashi, 2015; Knudsen et al., 2014; Nemecek et al., 2015). Some research has proposed Cereal Unit allocation to fully assess cropping systems, which is based on an agriculture-specific biophysical unit developed for the purpose of agricultural statistics (Brankatschk and Finkbeiner, 2014), and a methodology based on rotation allocation (Brankatschk and Finkbeiner, 2015). Other research studies proposed a dual approach by considering either each crop separately or the cropping system as a whole (Knudsen et al., 2014). Instead, Nemecek et al. (2015) considered the interval for each crop combination as starting after the harvest of the preceding crop and ending with the harvest of the main crop, together with assessing the cropping system as a whole.

Main LCA tools include SimaPro, GABI and OpenLCA which is an open source software under the Mozilla Public License (MPL 2.0) agreement. All these LCA tools were developed for general purposes including the agricultural sector. However they were not specifically designed to assess agricultural systems, and they do not readily consider effects of crop management on soil emissions (Ciroth, 2007; GABI, 2016; SimaPro 8.3, 2016). Thus, researchers and the private sector have developed several tools for agricultural LCA (BASF, 2015; Nemecek et al., 2015; Tuomisto et al., 2015). For instance, SALCA (Swiss Agricultural Life Cycle Assessment) was developed by Agroscope to assess agricultural systems mainly in Central Europe (Nemecek et al., 2015). AgBalance is another tool developed to carry out LCA of agricultural systems. However, the user cannot access or modify the code of either tool. In addition AgBalance, which was conceived for the sustainability assessment of agriculture, must be purchased by the user (BASF, 2015; Nemecek et al., 2010; Teuscher et al., 2014). In contrast, other tools, such as the European Union (EU) Carbon Calculator and ULICEES, were developed to compute carbon (C) footprints (Tuomisto et al., 2015; Vergé et al., 2012), while the FEAT model also included energy consumption (Camargo et al., 2013). Porta et al. (2008) developed eVerdEE, a simplified tool for environmental product declarations in the agricultural sector. Similarly, the Cranfield LCA tool was developed to assess agricultural systems under United Kingdom (UK) conditions using Microsoft® Excel (Williams et al., 2010), while the LCAD tool was specifically designed to assess anaerobic digestion systems (Styles et al., 2014, 2015). LCAcommons is both a set of tools and life cycle inventories (LCI) developed for different production processes, including agricultural products, by several United States (US) governmental institutions (USDA, 2015). The existing LCA tools developed to assess agriculture are either simple tools, not publicly available, not modular or not open-source, which is considered advantageous for the LCA community (Ciroth, 2007). In this study, a new adaptable open-source tool (Crop.LCA) to carry out screening LCA of cropping systems is i) presented, ii) tested in an evaluation study consisting of a scenario assessment of 4 cropping systems using an agroecosystem model to predict soil emissions (i.e., $CO_2$, $N_2O$, $CH_4$ and $NH_3$ volatilisation), and iii) used to compute the contribution of each process to overall 100-year horizon GWP.

# 2. Crop.LCA tool

## 2.1. General characteristics

The Crop.LCA tool was designed in 2015-2016 to perform screening LCA of cropping systems using local data according to ISO standards (ISO, 2006a, 2006b, 2013). Crop.LCA allows users to carry out site-specific assessment, as defined by Potting and Hauschild (2006), of the environmental impacts of cropping systems. It is open-source, community-based, and adaptable to a wide range of crops and types of crop management after collecting site specific data. Crop.LCA is at the same time a LCA software, it integrates models for nitrate leaching, soil P loss and soil erosion and allows to use model estimates or observations for GHG emissions to be accounted for in the life cycle assessment of cropping systems. The tool was developed by the authors, synthesising and integrating recent advances in agricultural LCA methodology with the aim of being flexible and specifically tailored for the assessment of agricultural systems. To serve as an adaptable software tool, Crop.LCA includes its source code, which users can modify. Figure 1 illustrates the framework of the tool, which can be used to rapidly perform screening LCA of cropping systems using 1 ha of land as the functional unit. Considering the recommendations given by Hayashi (2013) for food sustainable consumption and production and in agreement with Goglio et al. (2014) and Nemecek et al. (2011a), other functional units (kg of harvested product, GJ of harvested energy output, unit of economic value from agricultural production) can be computed from the value per ha generated by the tool for each impact category. The harvested energy output is the energy output of the grain yield and the amount of straw/residues harvested from the field. The current version of Crop.LCA computes the LCI of energy consumption and of key chemicals: fossil $CO_2$, biogenic $CO_2$, $CH_4$, $N_2O$, CO, $NH_3$, $NO_2$, $SO_2$, non-methane volatile organic compounds, particulate matter, $SF_6$, nitrate leaching, $PO_4^{-3}$, and phosphorus (P) emissions. Active ingredients for pesticides were considered only for the impact categories included in the tool, while heavy metals were excluded. The Crop.LCA tool uses the LCI to estimate CED according to Huijbregts et al. (2010), 100-year horizon GWP according to the Intergovernmental Panel for Climate Change (IPCC) 5th Assessment Report (Myhre et al., 2013), AP and EP according to the CML method (CML, 2015). The current version of Crop.LCA does not include any water-related impacts except EP. The tool also computes contributions to GWP of different processes (e.g., soil emissions of $CO_2$; $CH_4$ and

$N_2O$; machinery use, production and repair; fertiliser production and transport). If the results of soil $CO_2$ emissions are negative, it means that soil C sequestration occurred.

### 2.2. System boundary

The system boundary considered by Crop.LCA includes the agricultural phase, along with soil GHG emissions, $NH_3$ volatilisation, $NO_3^-$ leaching and all upstream processes, including machinery production, transport, maintenance and repairs, fertiliser, pesticide and seed production and transport (Fig. 2). The downstream limit is the transport of the agricultural products (e.g. grain, hay or silage) to the farm centre (i.e., location of the main farm facilities, including barns, silage pits and machinery storage facilities) (Fig. 2). Drying, silage pit filling, and hay storage are excluded. In agreement with previous research and ISO standards, all upstream processes from raw material extraction up to the regional storehouse (i.e. a building of the local suppliers of agricultural inputs) are included (Audsley et al., 1997; Brentrup et al., 2004; ISO, 2006a, 2006b, 2013). Transport processes from raw material extraction to the farm centre were included within the system boundary.

### 2.3. Data sources and treatment for the life cycle inventory

Field data are used as inputs to Crop.LCA. All upstream processes used emission factors derived from available literature. For instance, data for the production of fuel, electricity, steel, and rubber in Crop.LCA were derived from GHGenius ((S&T)2, 2014). GHGenius is a tool developed to account for environmental impacts of different vehicles in Canadian and US conditions with a cradle-to-wheel approach ((S&T)2, 2014). The data currently available in Crop.LCA for both background and foreground processes are relevant to North American conditions; however, data from other sources can be integrated in Crop.LCA by changing the corresponding input files available on the bitbucket platform (https://bitbucket.org/croplcateam/crop.lca), following the user manual and by collecting site-specific data for background processes. Data for seed, fertiliser and pesticide production were taken from other data sources (Bhatty et al., 1979; Boehmel et al., 2008; Brentrup et al., 2004; Ceccon et al., 2002; Gasol et al., 2012; Goglio et al., 2012; Hacıseferoğulları et al., 2003; (S&T)2, 2014). Urea and ammonia production data were derived from several data sources associated with North American conditions (Brentrup et al., 2004; Sheehan et al., 1998; (S&T)2, 2014). Data for inputs used during cultivation were treated as described below.

### 2.3.1. Machinery use, and machinery production, maintenance, and repairs

The machinery use LCI includes field operations, transport of machinery from the farm centre to the field, farm transport, and production and transport of the fuel necessary for both field operations and farm transport. Field operations are accounted for on the basis of field working capacity and the power needed to carry out the specific field operation (Dyer et al., 2010; Dyer and Desjardins, 2003). For farm transport with heavy-duty diesel trucks and light-duty petrol trucks, specific emissions and fuel consumption data from GHGenius were used ((S&T)2, 2014). For all agricultural diesel machinery, oil consumption was estimated on the basis of the ASABE standard D 497.7 (ASABE, 2011; Goglio et al., 2014). In all transport processes, the return journey of the machinery is included, in accordance with Gasol et al. (2012) and Goglio et al. (2012, 2014).

Machinery production impacts were estimated based on weight, working capacity, and total lifetime of the machine (ASABE, 2011; Audsley et al., 1997; Brentrup et al., 2004). Tractor production was computed using GHGenius ((S&T)2, 2014). Production impacts for machinery other than tractors were subdivided into material extraction impacts and those related to machinery manufacture, in accordance with Audsley et al. (1997) and Goglio et al. (2014). For manufacturing, electricity was the only energy source considered and the energy mix used was based on the location of the machinery factory (Audsley et al., 1997). This information was gathered by carrying out a survey of machinery manufacturers and suppliers in Canada, in agreement with Audsley et al., (1997) and Goglio et al. (2014).

Impacts of maintenance and repairs for machinery are included on the basis of the overall energy used during machinery manufacturing and the production of raw materials for machinery, in accordance with Audsley et al. (1997). In our accounting process, the overall energy is split among energy sources (e.g., electricity, diesel) to estimate total or cumulative energy consumption and emissions from maintenance and repair of machinery, and production of materials used during maintenance and repairs.

#### 2.3.2. Fertiliser, seed and pesticide production

Crop.LCA computes the LCI related to fertiliser use on the basis of the actual amount of fertiliser applied to fields. In the case of multiple fertilisers, the contribution of each component is considered in the production process. For instance, if a fertiliser is composed of urea and ammonium phosphate, the production of each is included. Seed production is computed on the basis of the number of seeds (maize, *Zea mays* L.) or the weight of seeds used during seeding. Pesticide production is accounted for on the basis of the amount of pesticide applied to fields, the type of pesticide or active ingredient, and its concentration. During pesticide transport, the quantity of the total formulation is used in calculations.

#### 2.3.3. Nitrate leaching, soil P loss, ammonia volatilisation and soil GHG emissions

Nitrate leaching is estimated for Crop.LCA by the SQCB (Sustainability Quick Check for Biofuels) model (Faist Emmenegger et al., 2009; Nemecek et al., 2014). Crop.LCA integrates the USLE (Universal Soil Loss Equation) to predict soil erosion according to Faist Emmenegger et al. (2009) and Nemecek et al. (2014). Soil P loss is estimated from soil erosion and the amount of P applied by integrating the SALCA-P model into Crop.LCA (Nemecek et al., 2010, 2014; Teuscher et al., 2014). Ammonia volatilisation and soil GHG emissions (i.e., $CO_2$, $CH_4$ emissions, $N_2O$) are read as inputs and included in computation of the LCI. In particular, Crop.LCA sums up GWP from all sources including $CO_2$ from soil C changes and computes soil $CO_2$ emissions in agreement with currently available LCA methods (Goglio et al., 2015). Crop.LCA predicts indirect $N_2O$ emissions from nitrate leaching and ammonia emissions using the IPCC Tier 1 method (De Klein et al., 2006).

### 2.4. Program design and availability

Crop.LCA was coded in the open-source program R (R Development Core Team, 2005) as a modular tool with separate functions for different processes (e.g., field cultivation, production and transport of fertiliser, nitrate leaching, soil GHG emissions, soil P loss). This allows the inclusion or exclusion of specific processes by disabling or enabling the functions in the source code. The open-source code and user manual are publicly available (https://bitbucket.org/croplcateam/crop.lca). The R code can be readily modified, and the input files can be edited in a spreadsheet following the user manual. All input files are in comma separated value (.csv) format. For background processes, Crop.LCA uses data from literature and other databases (e.g., GHGenius)(S&T)2, 2014). Other modules in Crop.LCA have also been designed to compute GWP, EP, and AP.

# 3. Evaluation study

## 3.1. Case study scenario assessment

A case study was used to validate Crop.LCA, based on a scenario assessment of 4 cropping systems studied in a field experiment described by Glenn et al. (2010, 2011, 2012) and Maas et al. (2013), located at the Glenlea Research Station (49.64°N, 97.16°W; 235 m a.s.l.), on the Red River plain (<2% slope) near Winnipeg, Manitoba, Canada. Mean soil organic C content (0–0.2 m) at the beginning of the study was approximately 3.2%. Particle size distribution was 60% clay, 35% silt, and 5% sand. The impact categories and system boundary considered in the LCA are the same as those in Crop.LCA. The functional units used are ha of land and GJ of gross energy output.

The conventional (CONV) cropping system (Table 1) has a crop management system similar to that of the annual cropping system described by Glenn et al. (2010, 2011, 2012). The CONV, no-tillage (NT), and residue (RES) systems include the same crop sequence with no cover crops (maize-spring wheat (*Triticum aestivum* L.)-canola (*Brassica napus* L.)-spring barley (*Hordeum vulgare* L.)), while in the legume (L) system, faba bean (*Vicia faba* var. *minor* L.) replaces maize (Table 1). In the RES system, straw and maize stover are left in the field, unlike in the other systems (Table 1). Full details can be found in the supplementary material.

For the scenario assessment, a Canadian version (DNDC v.CAN) (Grant et al., 2016; Kröbel et al., 2011; Smith et al., 2013) of the DNDC (Denitrification and Decomposition) model (Li et al., 1992, 1994) was run using 28 years (1985–2012) of climate data (i.e., daily max. and min. temperature, precipitation, global solar radiation, humidity and wind speed). DNDC estimates of GHG emissions, grain yields, crop residues, and nitrate and ammonia losses were used as inputs for the Crop.LCA tool. Yearly data ($1^{st}$ Jan –$31^{st}$ Dec) for each impact category were aggregated to compute a mean impact for each 4-year rotation (e.g., 1985–1988, 1989–1992) of the cropping systems to have 7 sample elements for statistical analysis. Yearly data were used, as all of the crops have a similar life cycle (~150-day growth, spring sown with fall harvest). Only 2% of the harvested area of crops in the study region is sown in autumn (CANSIM, 2016). However, Crop.LCA can compute impacts for different timeframes when necessary (e.g. harvest of the previous crop to harvest of the given crop). The impacts for spring wheat were also calculated separately, since it is a major crop in the region (CANSIM, 2016). The harvested energy output (GJ) is computed from yields and the upper heating value (or gross energy) of the harvested biomass.

### 3.2. DNDC model and simulations

DNDC was originally developed to estimate $N_2O$ emissions (Li et al., 1992), but it has been expanded to simulate soil C and nitrogen (N) dynamics and $CO_2$ emissions (Li et al., 1994). The model has been developed and tested for many soils, climates, and cropping systems. Several regional versions are available on the Global Research Alliance Modelling Platform (http://gramp.org.uk/models/family/2). DNDC (DNDCv.CAN) was first run for 10 years to stabilise C and N pools before estimating soil GHG emissions for each system. The climate data, crop, and soil inputs for the simulations were obtained from Uzoma et al. (2015), who found DNDC reasonably simulated soil temperature, soil water content, soil N, and $N_2O$ emissions for annual cropping.

### 3.3. Statistical analyses

Statistical analyses were conducted with R to investigate whether i) the CED, GWP, AP, and EP of the cropping systems and ii) the GWP of wheat, for both functional units (ha and GJ), were statistically different. A Friedman test was first performed, followed by pair-wise non-parametric comparisons, considering each 4-year rotation separately for the entire cropping system assessment and each year of wheat cultivation separately (Siegel and Castellan, 1988). There were thus 7 sample elements (i.e., 4-year rotation average) available for the statistical analyses, while one value for each 4-year rotation was used to assess impacts of wheat cultivation. Crop.LCA was also used to perform contribution analysis of soil emissions.

### 3.4. Results

The L cropping system had the lowest mean GWP per ha (3740 kg $CO_2$eq $ha^{-1}$ $y^{-1}$, Fig. 3a), 23% less than that in the CONV system. In contrast, wheat in the RES system had the lowest mean GWP per ha (1670 kg $CO_2$eq $ha^{-1}$ $y^{-1}$, Fig. 3c), with high variability due to the interaction of climate, soil and crop management. Per GJ, GWP for wheat in the RES system also had high variability (Fig. 3d). Considering the entire cropping systems, the NT and CONV systems had the lowest mean GWP per GJ (34 and 38 kg $CO_2$ eq $GJ^{-1}y^{-1}$, respectively) (Fig. 3b). Statistical tests confirmed that these differences in GWP were significant for both functional units at $p<0.05$, except for GWP per GJ of wheat (Fig. 3d). GWP was strongly affected by soil C dynamics, which influenced soil $CO_2$ emissions (-230% of GWP, on average; range = -9.8% to -391% depending upon the cropping system assessed); the negative sign indicates a reduction in GWP due to $CO_2$ absorption of the crop from the atmosphere and the consequent increase in soil C from retained residues. The contribution of direct $N_2O$ emissions to GWP averaged 171% among the systems while the mean contribution of the indirect $N_2O$ emissions to GWP was smaller (12%).

The CONV system had the highest mean CED per ha (19.2 GJ $ha^{-1}$ $y^{-1}$) (Fig. 4a), while the L system had the lowest (19% less than that in CONV). The NT system had the lowest mean CED per GJ of energy output (0.153 GJ $GJ^{-1}$ $y^{-1}$), 2.4% less than that in the CONV system (Fig. 4b). These differences among cropping systems were statistically significant for both functional units at $p<0.05$. There was little difference in EP per ha among the 4 cropping systems (Fig 4c). The L system had the lowest mean EP (19.1 kg of $PO_4^{-3}$eq $ha^{-1}$ $y^{-1}$), 4.5% less than that in the CONV system. For EP per GJ, the NT system had the lowest EP (0.157 kg of $PO_4^{-3}$eq $GJ^{-1}$ $y^{-1}$, Fig. 4d), 3.5% less than that in the CONV system. The RES system had the highest mean AP per ha (32.3 kg $SO_2$eq $ha^{-1}$ $y^{-1}$, Fig. 4e), 13.4% higher than that in the CONV system, while the L system had 18.8% less AP than the CONV system. In line with AP per ha, mean AP per GJ was highest in the RES system (0.565 kg $SO_2$eq $GJ^{-1}$ $y^{-1}$,Fig. 4f), 68.0% higher than that in the CONV system, while the NT system had the lowest AP (0.199 kg of $SO_2$eq $GJ^{-1}$ $y^{-1}$), 14.3% less than that in the CONV system. Differences in AP and EP were statistically significant for both functional units at $p<0.05$.

## 4. Discussion

### 4.1. Scenario assessment

The scenario assessment demonstrated the ability of Crop.LCA to capture characteristics of these different cropping-system scenarios. Introduction of legumes into the cropping system reduced most of the impacts considered. In particular, the cropping system with legumes decreased CED by at least 3.9%, GWP by 23.0%, and AP by 19% per ha.

Values of CED per ha (13-19 GJ $ha^{-1}$ $y^{-1}$) were close to the range of values reported by Pelletier et al. (2008) for organic and conventional wheat, maize, and canola (1.9-17 GJ $ha^{-1}$ $y^{-1}$) on the basis of average Canadian conditions for cultivation and using statistical data. CED per GJ (0.15-0.32 GJ $GJ^{-1}$) agreed with results obtained by Goglio et al. (2014) (0.25-0.39 GJ $GJ^{-1}$) using SimaPro and DNDC model results for two locations in western Canada with climate and soil similar to those of the present study.

The GWP obtained with Crop.LCA are similar to those of other LCAs of cropping systems using emission factors and models to estimate soil GHG emissions and reactive N species, but other research often disregard soil C dynamics (Bacenetti et al., 2014; Börjesson and Tufvesson, 2011; Brentrup et al., 2004; Goglio et al., 2014; Kim et al., 2009; Nemecek et al., 2011b, 2011a). Several C footprint studies have been conducted under similar conditions (Dyer et al., 2010; Dyer and Desjardins, 2003; Shrestha et al., 2013, 2014). Most Crop.LCA estimates of GWP are higher than the C footprints reported from these studies due to soil GHG accounting methods (in particular for soil $N_2O$ and soil $CO_2$ emissions) and system boundaries (inclusion of soil borne emissions) which differ from those in the present study. The contribution analysis revealed the importance of soil emissions to total GWP. For the cropping systems assessed here, the contribution of soil C change to the GWP was -230%, while direct $N_2O$ emissions contributed 171% of the GWP on average. In Crop.LCA soil emissions can be accounted for by including them as inputs (i.e. from different sources: measurements, models, emission factors). This is an interesting feature of the tool, considering the high level contribution of soil emissions in the overall GWP of cropping system (Garrigues et al., 2012; Goglio et al., 2014). These results are larger than those of Zaher et al. (2013), who reported up to a 70% contribution of direct $N_2O$

emissions to overall GWP in a cropping system containing wheat and barley in eastern Washington, US.

The EP results per ha (19-21 kg $PO_4^{3-}$eq $ha^{-1}$) are in line with those of other LCA studies for similar crops (e.g., wheat and maize) (17-58 kg $PO_4^{3-}$eq $ha^{-1}$) (Bacenetti et al., 2015; Goglio et al., 2012) under different soil and climate conditions. The EP for the entire cropping system was at least 24% larger than those obtained for maize cultivation at several locations in the US maize belt (Kim et al., 2009) using the DAYCENT model, most likely due to different methods used to estimate nitrate leaching.

The AP results per ha lie within the range of those reported by Kim et al. (2009) for US maize production using DAYCENT (22-53 kg $SO_2$eq $ha^{-1}$ $y^{-1}$). However, AP per ha in the current study was at least 5.4 times as large as the AP reported by Goglio et al. (2012), who performed an LCA of cropping systems, including maize and wheat, in Mediterranean conditions. In contrast, AP per ha was >55% lower than the AP reported by Bacenetti et al. (2015) for maize cultivation in northern Italy. The results obtained in this study demonstrate the strong influence that crop selection can have on the overall performance of cropping systems (Camargo et al., 2013; Gan et al., 2011; MacWilliam et al., 2014; Nemecek et al., 2015), highlighting the importance of designing sustainable cropping systems within the context of a bio-economy.

### 4.2. Comparison with other LCA tools

Open-source LCA tools are highly sought within the LCA community (Ciroth, 2007)  because they increase transparency, which hastens development. Having full access to the source code, the LCA user can modify functions as required, which was previously suggested as advantageous for the openLCA tool (Ciroth, 2007). The availability of the source code gives more flexibility, which is necessary to account for variability, which is common in agricultural systems (Börjesson and Tufvesson, 2011). Among the tools assessed, only Crop.LCA and the FEAT model are open-source (Table 2). However, the FEAT model is not modular, does not allow a multi-approach assessment, where a single crop and a cropping system are assessed at the same time and does not incorporate multiple methods to account for soil emissions (Camargo et al., 2013).

Crop.LCA was developed with a modular framework, which makes it easy to use from a programming standpoint, as with SALCA and the EU Carbon Calculator (Nemecek et al., 2010, 2015; Teuscher et al., 2014; Tuomisto et al., 2015) (Table 2). The modular framework also allows exclusion or inclusion of specific processes (e.g., machinery production, fertiliser application) by enabling and disabling the corresponding functions in the source code. Crop.LCA can therefore be rapidly adapted to different goals and scopes of agricultural LCA (Teuscher et al., 2014). The Crop.LCA tool can assess entire cropping systems over several years as a single entity, or individual crops, which is considered important (Brankatschk and Finkbeiner, 2015; Knudsen et al., 2014; Nemecek et al., 2015). In contrast with Crop.LCA, SALCA does not account for more than one input method to account for soil  emissions and is not adaptable, while the EU Carbon Calculator considers only GWP, excludes other impact categories and does not allow multiple methods  to be used for soil  emissions (Table 2) (Tuomisto et al., 2015).

Crop.LCA is publicly available online, can be run in R with few commands, and uses .csv files. The user-friendly framework is similar to that of the SALCA and LCAD tools, the FEAT model and the EU Carbon Calculator, which are Excel-based macros. It is also similar to the eVerdEE tool, which includes a graphical user interface (Table 2) (Camargo et al., 2013; Nemecek et al., 2010; Porta et al., 2008; Styles et al., 2014, 2015; Teuscher et al., 2014; Tuomisto et al., 2015).

Unlike some previous tools developed for LCA or C footprint assessment, Crop.LCA includes other impact categories besides GWP, such as EP and AP (Camargo et al., 2013; Dyer and Desjardins, 2003; Tuomisto et al., 2015; Vergé et al., 2012) (Table 2). Furthermore, it was developed in compliance with ISO standards (ISO, 2006a, 2006b, 2013), focuses on crop management and applies characterization factors from the IPCC 5$^{th}$ Assessment Report (Myhre et al., 2013).

Crop.LCA is a comprehensive tool which can characterise field operations, depending on the type of machinery used, its weight and power. It shares these features with SALCA, but uses a more complex approach than eVerdEE (Nemecek et al., 2010; Porta et al., 2008; Teuscher et al., 2014). Crop.LCA has the potential to be adapted by the user to carry out LCA of a wide range of crops, including catch crops, cover crops, and other temperate and tropical crops. For this reason, it can be used to assess bio-economic systems involving many products and production pathways (Philp, 2015). The current version of Crop.LCA cannot represent as many crops as several other tools (BASF, 2015; Camargo et al., 2013; Nemecek et al., 2010; Porta et al., 2008; Styles et al., 2014, 2015; Teuscher et al., 2014) (Table 2); however, they contain other limitations when compared with Crop.LCA. For instance, SALCA currently focuses on Swiss and central European systems. Other models can be used worldwide, such as AgBalance, eVerdEE, the FEAT model, and LCAD (BASF, 2015; Camargo et al., 2013; Porta et al., 2008; Styles et al., 2014, 2015). Crop.LCA can also be integrated to carry out either spatialised or regional LCA.

One limitation of Crop.LCA is that it is based mostly on North American conditions (Table 2). In addition like some other tools (USDA, 2015; Vergé et al., 2012), life cycle inventory analysis of the background processes was not part of the original development objectives of Crop.LCA. Thus, input data files for unit processes for background processes (e.g., the production of fertilizers, pesticides, seeds), occurring outside North American conditions, are currently not available and need to be prepared by the LCA practictioner using other software and databases (e.g., SimaPro, (SimaPro 8.3, 2016)) to conduct site-specific assessments. However, being open-source, users can select geographically specific input files (e.g. soils and impact factors) or use empirical data. Furthermore, users can develop the code to include other impacts, processes, data sources or features. Many calculation libraries are available in R, which offers the adaptability needed for assessing new bio-economic systems and current systems in new ways.

## 4. Conclusion

Crop.LCA can capture the interactions of soil, climate and crop management for a variety of cropping systems. The main strength of Crop.LCA is that it is transparent and open-source; therefore, the code can be modified by the LCA practitioner as needed. The availability of the source code provides more flexibility, which is necessary to account for variability in agricultural systems. Crop.LCA can also be used for site-specific assessments, increasing the accuracy of bio-economic assessments. The tool has the advantage of accounting for several substances, allowing for the assessment of individual crops or cropping systems over several years. Further developments should include the introduction of new substances and impact categories.

In the scenario assessment, Crop.LCA captured variability among cropping-system scenarios. It highlighted the environmental benefits of introducing legumes in rotation. It also demonstrated that inclusion of soil C change significantly reduced the GWP of cropping systems; thus, it should be included in the assessment of bio-economic systems. Further developments are necessary to better estimate impacts of crop-management choices in the assessment of bio-economic systems, integrating scientific evidence provided by agricultural and bioenergy research in LCA methodology.

## 5. Acknowledgements

The authors would like to acknowledge Dr. Constantine A. Campbell and Andrea De Angeli for their interesting scientific discussions and Don O'Connor for his valuable insight and support. Funds from the Agricultural Greenhouse Gas Program of Agriculture and Agri-Food Canada (AGGP-AAFC) were provided to MT for gathering and analysing the Manitoba site data. The authors acknowledge AAFC and the Natural Sciences and Engineering Research Council of Canada for funding PG's Visiting Fellowship.

## 6. References

ASABE, 2011. ASAE D497.7 MAR 2011 Agricultural Machinery Management Data. American Society of Agricultural and Biological Engineers, St. Joseph, Michigan.

Audsley, E., Alber, S., Clift, R., Cowell, S., Crettaz, P., Gaillard, G., Hausheer, J., Jolliett, O., Kleijn, R., Mortensen, B., Pearce, D., Roger, E., Teulon, H., Weidema, B., van Zeijts, H., 1997. Harmonisation of environmental life cycle assessment for agriculture. Final Report. Concerted action AIR3-CT94-2028. Silsoe Research Institute; Brussels: European Commission DG VI Agriculture, Silsoe.

Bacenetti, J., Fusi, A., Negri, M., Guidetti, R., Fiala, M., 2014. Environmental assessment of two different crop systems in terms of biomethane potential production. Sci. Tot. Environ. 466–467, 1066–1077. doi: 10.1016/j.scitotenv.2013.07.109

Bacenetti, J., Fusi, A., Negri, M., Fiala, M., 2015. Impact of cropping system and soil tillage on environmental performance of cereal silage productions. J. Clean Prod. 86, 49–59. doi: 10.1016/j.jclepro.2014.08.052

BASF, 2015. AgBalance - Measuring Sustainability in Agriculture. BASF Crop Protection. BASF Badische Anilin- und Soda-Fabrik, Ludwigshafen, Germany. Available at: URL http://www.agro.basf.com/agr/AP-Internet/en/content/sustainability/measuring_sustainability/agbalance/index. (Accessed: 28.07.2015)

Bhatty, R.S., Rossnagel, B.G., Christison, G.I., 1979. Energy and protein digestibilities of hulled and hulless barley determined by swine-feeding. Can. J. Anim. Sci. 59, 585–588. doi: 10.4141/cjas79-073

Biswas, W.K., Barton, L., Carter, D., 2008. Global warming potential of wheat production in Western Australia: a life cycle assessment. Water and Env. J. 22, 206–216. doi: 10.1111/j.1747-6593.2008.00127.x

Boehmel, C., Lewandowski, I., Claupein, W., 2008. Comparing annual and perennial energy cropping systems with different management intensities. Agr. Syst. 96, 224–236. doi: 10.1016/j.agsy.2007.08.004

Börjesson, P., Tufvesson, L.M., 2011. Agricultural crop-based biofuels – resource efficiency and environmental performance including direct land use changes. J. Clean Prod. 19, 108–120. doi: 10.1016/j.jclepro.2010.01.001

Bosch, R., Van de Pol, M., Philp, J., 2015. Define biomass sustainability. Nat. 523, 526–527.

Brankatschk, G., Finkbeiner, M., 2014. Application of the Cereal Unit in a new allocation procedure for agricultural life cycle assessments. J. Clean Prod. 73, 72–79. doi: 10.1016/j.jclepro.2014.02.005

Brankatschk, G., Finkbeiner, M., 2015. Modeling crop rotation in agricultural LCAs — Challenges and potential solutions. Agr. Syst. 138, 66–76. doi: 10.1016/j.agsy.2015.05.008

Brentrup, F., Küsters, J., Lammel, J., Barraclough, P., Kuhlmann, H., 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment (LCA) methodology II. The application to N fertilizer use in winter wheat production systems. Eur. J. Agr. 20, 265–279. doi: 10.1016/S1161-0301(03)00039-X

Camargo, G.G.T., Ryan, M.R., Richard, T.L., 2013. Energy use and greenhouse gas emissions from crop production using the Farm Energy Analysis Tool. BioSci 63, 263–273. doi: 10.1525/bio.2013.63.4.6

CANSIM, S.C., 2016. CANSIM Table 001-0010. Estimated areas, yield, production and average farm price of principal field crops, in metric units, annual. http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=0010010&&pattern=&stByVal=1&p1=1&p2=31&tabMode=dataTable&csid=/ (accessed 14.03.2016).

Ceccon, P., Coiutti, C., Giovanardi, R., 2002. Energy Balance of Four Farming Systems in North-Eastern Italy. Ital. J. Agron. 6, 73–83.

Ciroth, A., 2007. ICT for environment in life cycle applications openLCA — A new open source software for life cycle assessment. Int. J. Life Cycle Assess. 12, 209–210. doi: 10.1065/lca2007.06.337

CML, 2015. CML-IA Characterisation Factors - Software and data - CML. Universiteit Leiden, Leiden. Available at: URL http://cml.leiden.edu/software/data-cmlia.html. (Accessed: 20.07.2015)

De Klein, C., Novoa, R.S.A., Ogle, S., Smith, K.A., Rochette, P., Wirth, T.C., McConkey, B.G., Mosier, A., Rypdal, K., Walsh, M., Williams, S.A., 2006. Chapter 11: N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application, in: Gytarsky M, Hiraishi T, Irving W, Krug T, Penman J (Eds.), IPCC Guidelines for National Greenhouse Gas Inventories. IPCC International Panel on Climate Change, Geneva, p. 11.1-11.54.

Dyer, J.A., Desjardins, R.L., 2003. Simulated Farm Fieldwork, Energy Consumption and Related Greenhouse Gas Emissions in Canada. Biosyst. Eng. 85, 503–513. doi: 10.1016/S1537-5110(03)00072-2

Dyer, J.A., Vergé, X.P.C., Desjardins, R.L., Worth, D.E., McConkey, B.G., 2010. The impact of increased biodiesel production on the greenhouse gas emissions from field crops in Canada. Energy Sustain. Dev. 14, 73–82. doi: 10.1016/j.esd.2010.03.001

Faist Emmenegger, M., Reinhard, J., Zah, R., Ziep, T., Weichbrodt, R., Wohlgemuth, V., Berlin, F., Roches, A., Freiermuth Knuchel, R.F., Gaillard, G., 2009. Sustainability Quick Check for Biofuels. Agroscope Reckenholz-Tänikon, Dübendorf.

GABI, 2016. GABI Envision software 2.5 Gabi, Leinfelden-EchterdingenGermany.

Gan, Y., Liang, C., Hamel, C., Cutforth, H., Wang, H., 2011. Strategies for reducing the carbon footprint of field crops for semiarid areas. A review. Agron. Sustain. Dev. 31, 643–656. doi: 10.1007/s13593-011-0011-7

Garrigues, E., Corson, M.S., Angers, D.A., van der Werf, H.M.G., Walter, C., 2012. Soil quality in Life Cycle Assessment: Towards development of an indicator. Ecological Indicators 18, 434–442. doi: 10.1016/j.ecolind.2011.12.014

Gasol, C.M., Salvia, J., Serra, J., Antón, A., Sevigne, E., Rieradevall, J., Gabarrell, X., 2012. A life cycle assessment of biodiesel production from winter rape grown in Southern Europe. Biomass Bioenerg. 40, 71–81. doi: 10.1016/j.biombioe.2012.02.003

Glenn, A.J., Amiro, B.D., Tenuta, M., Stewart, S.E., Wagner-Riddle, C., 2010. Carbon dioxide exchange in a northern Prairie cropping system over three years. Agr. Forest Meteorol. 150, 908–918. doi: 10.1016/j.agrformet.2010.02.010

Glenn, A.J., Amiro, B.D., Tenuta, M., Wagner-Riddle, C., Drewitt, G., Warland, J., 2011. Contribution of crop residue carbon to soil respiration at a northern Prairie site using stable isotope flux measurements. Agr. Forest Meteorol. 151, 1045–1054. doi: 10.1016/j.agrformet.2011.03.008

Glenn, A.J., Tenuta, M., Amiro, B.D., Maas, S.E., Wagner-Riddle, C., 2012. Nitrous oxide emissions from an annual crop rotation on poorly drained soil on the Canadian Prairies. Agr. Forest Meteorol. 166–167, 41–49. doi: 10.1016/j.agrformet.2012.06.015

Goglio, P., Bonari, E., Mazzoncini, M., 2012. LCA of cropping systems with different external input levels for energetic purposes. Biomass Bioenerg. 42, 33–42. doi: 10.1016/j.biombioe.2012.03.021

Goglio, P., Grant, B.B., Smith, W.N., Desjardins, R.L., Worth, D.E., Zentner, R., Malhi, S.S., 2014. Impact of management strategies on the global warming potential at the cropping system level. Sci. Tot. Environ. 490, 921–933. doi: 10.1016/j.scitotenv.2014.05.070

Goglio, P., Smith, W.N., Grant, B.B., Desjardins, R.L., McConkey, B.G., Campbell, C.A., Nemecek, T., 2015. Accounting for soil carbon changes in agricultural life cycle assessment (LCA): a review. J. Clean Prod. 104, 23–39. doi: 10.1016/j.jclepro.2015.05.040

Grant, B., Smith, W., Campbell, C., Desjardins, R., Lemke, R., Kroebel, R., McConkey, B., Smith, E., Lafond, G., 2016. Comparison of DayCent and DNDC models: Case studies using data from long-term experiments on the Canadian prairies, in: Del Grosso S, Parton B, Lajpat A (Eds.), Advances in Modeling Agricultural Systems: Trans-Disciplinary Research, Synthesize, Modeling, and Applications., ASA-SSSA-CSSA Book Series. Madison.

Hacıseferoğulları, H., Gezer, İ., Bahtiyarca, Y., Mengeş, H.O., 2003. Determination of some chemical and physical properties of Sakız faba bean (Vicia faba L. Var. major). J. Food Eng. 60, 475–479. doi: 10.1016/S0260-8774(03)00075-X

Hayashi, K., 2013. Practical recommendations for supporting agricultural decisions through life cycle assessment based on two alternative views of crop production: the example of organic conversion. Int. J. Life Cycle Assess. 18, 331–339. doi: 10.1007/s11367-012-0493-9

Hokazono, S., Hayashi, K., 2015. Life cycle assessment of organic paddy rotation systems using land- and product-based indicators: a case study in Japan. Int. J. Life Cycle Assess. 20, 1061–1075. doi: 10.1007/s11367-015-0906-7

Huijbregts, M.A.J., Hellweg, S., Frischknecht, R., Hendriks, H.W.M., Hungerbühler, K., Hendriks, A.J., 2010. Cumulative Energy Demand As Predictor for the Environmental Burden of Commodity Production. Environ. Sci. Technol. 44, 2189–2196. doi: 10.1021/es902870s

Huisingh, D., Zhang, Z., Moore, J.C., Qiao, Q., Li, Q., 2015. Recent advances in carbon emissions reduction: policies, technologies, monitoring, assessment and modeling.

Journal of Cleaner Production, Carbon Emissions Reduction: Policies, Technologies, Monitoring, Assessment and Modeling 103, 1–12. doi: 10.1016/j.jclepro.2015.04.098

ISO, 2006a. SS-EN ISO 14040 Environmental Management- Life Cycle Assessment, Principles and Framework. International Organization for Standardization, Geneva.

ISO, 2006b. SS-EN ISO 14044 Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization, Geneva.

ISO, 2013. TS-EN ISO 14067 Greenhouse Gases -Carbon Footprint of Products- Requirements and Guidelines for Quantification and Communication. International Organization for Standardization, Geneva.

Kim, S., Dale, B.E., Jenkins, R., 2009. Life cycle assessment of corn grain and corn stover in the United States. Int. J. Life Cycle Assess. 14, 160–174. doi: 10.1007/s11367-008-0054-4

Knudsen, M.T., Meyer-Aurich, A., Olesen, J.E., Chirinda, N., Hermansen, J.E., 2014. Carbon footprints of crops from organic and conventional arable crop rotations - Using a life cycle assessment approach. J. Clean Prod. 64, 609–618. doi: 10.1016/j.jclepro.2013.07.009

Kröbel, R., Smith, W., Grant, B., Desjardins, R., Campbell, C., Tremblay, N., Li, C., Zentner, R., McConkey, B., 2011. Development and evaluation of a new Canadian spring wheat sub-model for DNDC. Can. J. Soil Sci. 91, 503–520. doi: 10.4141/cjss2010-059

Li, C., Frolking, S., Frolking, T.A., 1992. A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. J. Geophys. Res. 97, 9759–9776. doi: 10.1029/92JD00509

Li, C., Frolking, S., Harriss, R., 1994. Modeling carbon biogeochemistry in agricultural soils. Global Biogeochem. Cycles 8, 237–254. doi: 10.1029/94GB00767

Maas, S.E., Glenn, A.J., Tenuta, M., Amiro, B.D., 2013. Net $CO_2$ and $N_2O$ exchange during perennial forage establishment in an annual crop rotation in the Red River Valley, Manitoba. Can. J. Soil Sci. 93, 639–652. doi: 10.4141/cjss2013-025

MacWilliam, S., Wismer, M., Kulshreshtha, S., 2014. Life cycle and economic assessment of Western Canadian pulse systems: The inclusion of pulses in crop rotations. Agric. Syst. 123, 43–53. doi: 10.1016/j.agsy.2013.08.009

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, D., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and Natural Radiative Forcing, in: Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., pp. 659–740.

Nemecek, T., Freiermuth Knuchel, R., Alig, M., Gaillard, G., 2010. The advantages of generic LCA tools for agriculture: examples SALCAcrop and SALCAfarm. Presented at the 7 th International Conference on Life Cycle Assessment in Agri-Food sector, Bari.

Nemecek, T., Dubois, D., Huguenin-Elie, O., Gaillard, G., 2011a. Life cycle assessment of Swiss farming systems: I. Integrated and organic farming. Agr. Syst. 104, 217–232. doi: 10.1016/j.agsy.2010.10.002

Nemecek, T., Huguenin-Elie, O., Dubois, D., Gaillard, G., Schaller, B., Chervet, A., 2011b. Life cycle assessment of Swiss farming systems: II. Extensive and intensive production. Agr. Syst. 104, 233–245. doi: 10.1016/j.agsy.2010.07.007

Nemecek, T., Bengoa, X., Lansche, J., Mouron, P., Rossi, V., Humbert, S., 2014. Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. Version 2.0. World Food LCA Database (WFLDB). Quantis and Agroscope, Lausanne and Zurich, Switzerland.

Nemecek, T., Hayer, F., Bonnin, E., Carrouée, B., Schneider, A., Vivier, C., 2015. Designing eco-efficient crop rotations using life cycle assessment of crop combinations. Eur. J. Agron. 65, 40–51. doi: 10.1016/j.eja.2015.01.005

Pelletier, N., Arsenault, N., Tyedmers, P., 2008. Scenario Modeling Potential Eco-Efficiency Gains from a Transition to Organic Agriculture: Life Cycle Perspectives on Canadian Canola, Corn, Soy, and Wheat Production. Environ. Manag. 42, 989–1001. doi: 10.1007/s00267-008-9155-x

Philp, J., 2015. Balancing the bioeconomy: supporting biofuels and bio-based materials in public policy. Energy Environ. Sci. 8, 3063–3068. doi: 10.1039/C5EE01864A

Porta, P., Buttol, P., Naldesi, L., Masoni, P., Zamagni, A., 2008. A simplified LCA tool for Environmental Product Declarations in the agricultural sector. Presented at the 6th International Conference on LCA in the Agri-Food sector, Zurich, pp. 318–324.

Potting, J., Hauschild, M.Z., 2006. Spatial differentiation in life cycle impact assessment: A decade of method development to increase the environmental realism of LCIA. Int. J. Life Cycle Assess. 11, 11–13. doi: 10.1065/lca2006.04.005

Pülzl, H., Kleinschmit, D., Arts, B., 2014. Bioeconomy – an emerging meta-discourse affecting forest discourses? Scand. J. Forest Res. 29, 386–393. doi: 10.1080/02827581.2014.920044

R Development Core Team, 2005. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., Shapouri, H., 1998. Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus ( No. NREL/SR-580-24089). U.S. Department of Energy’s Office of Fuels Development; U.S. Department of

Agriculture's Office of Energy; National Renewable Energy Laboratory; Midwest Research Institute, US.

Shrestha, B.M., McConkey, B.G., Smith, W.N., Desjardins, R.L., Campbell, C.A., Grant, B.B., Miller, P.R., 2013. Effects of crop rotation, crop type and tillage on soil organic carbon in a semiarid climate. Can. J. Soil Sci. 93, 137–146. doi: 10.4141/cjss2012-078

Shrestha, B.M., Desjardins, R.L., McConkey, B.G., Worth, D.E., Dyer, J.A., Cerkowniak, D.D., 2014. Change in carbon footprint of canola production in the Canadian Prairies from 1986 to 2006. Renew. Energy 63, 634–641.

Siegel, S., Castellan, N., 1988. Nonparametric statistics for behavioral sciences, McGraw-Hill. ed. New York.

SimaPro 8.3, 2016. Simapro 8.3. PRé Consultants: Life Cycle consultancy and software solutions, Amersfoort, Netherlands.

Smith, W.N., Grant, B.B., Desjardins, R.L., Kroebel, R., Li, C., Qian, B., Worth, D.E., McConkey, B.G., Drury, C.F., 2013. Assessing the effects of climate change on crop production and GHG emissions in Canada. Agric. Ecosyst. Environ. 179, 139–150. doi: 10.1016/j.agee.2013.08.015

(S&T)2, 2014. GHGenius, Model Version 4.03a. (S&T)2 Consultants Inc. for Natural Resources Canada, Delta, British Columbia, Canada. http://www.ghgenius.ca/ (Accessed 25.06.2014).

Styles, D., Gibbons, J., Williams, A.P., Stichnothe, H., Chadwick, D.R., Healey, J.R., 2014. Cattle feed or bioenergy? Consequential life cycle assessment of biogas feedstock options on dairy farms. GCB Bioenergy 7, 1034–1049. doi: 10.1111/gcbb.12189

Styles, D., Gibbons, J., Williams, A.P., Dauber, J., Stichnothe, H., Urban, B., Chadwick, D.R., Jones, D.L., 2015. Consequential life cycle assessment of biogas, biofuel and biomass energy options within an arable crop rotation. GCB Bioenergy 7, 1305–1320. doi: 10.1111/gcbb.12246

Teuscher, R., Lansche, J., Nemecek, T., Gaillard, G., 2014. Optimizing the LCA data processing for food products in the context of Life Cycle Sustainability Assessment: challenges and opportunities. Presented at the 9th Conference on Life Cycle Assessment in the Agri-Food Sector, San Francisco.

Tuomisto, H.L., De Camillis, C., Leip, A., Nisini, L., Pelletier, N., Haastrup, P., 2015. Development and testing of a European Union-wide farm-level carbon calculator. Integr. Environ. Assess. Manag. 11, 404–416. doi: 10.1002/ieam.1629

USDA, 2015. LCA Digital Commons Project. United States Department of Agriculture. Available at: URL http://www.lcacommons.gov/?q=about. (Accessed: 29.07.2015).

Uzoma, K.C., Smith, W., Grant, B., Desjardins, R.L., Gao, X., Hanis, K., Tenuta, M., Goglio, P., Li, C., 2015. Assessing the effects of agricultural management on nitrous oxide emissions using flux measurements and the DNDC model. Agric. Ecosyst. Environ. 206, 71–83. doi: 10.1016/j.agee.2015.03.014

Vergé, X.P.C., Dyer, J.A., Worth, D.E., Smith, W.N., Desjardins, R.L., McConkey, B.G., 2012. A Greenhouse Gas and Soil Carbon Model for Estimating the Carbon Footprint of Livestock Production in Canada. Anim. 2, 437–454. doi: 10.3390/ani2030437

Williams, A.G., Audsley, E., Sandars, D.L., 2010. Environmental burdens of producing bread wheat, oilseed rape and potatoes in England and Wales using simulation and system modelling. Int. J. Life Cycle Assess. 15, 855–868. doi: 10.1007/s11367-010-0212-3

World Bank, 2015. Population growth (annual %) | Data | Table. http://data.worldbank.org/indicator/SP.POP.GROW. (Accessed at: 11.11.2015).

Zaher, U., Stöckle, C., Painter, K., Higgins, S., 2013. Life cycle assessment of the potential carbon credit from no- and reduced-tillage winter wheat-based cropping systems in Eastern Washington State. Agric. Syst. 122, 73–78. doi: 10.1016/j.agsy.2013.08.004

## Figure captions

**Figure 1 Conceptual framework of the Crop.LCA tool (NPKS: fertiliser; LCA.ini(), name of the initialisation function to start Crop.LCA in the R environment; CED: Cumulative Energy Demand; GWP: global warming potential with a 100 year horizon; AP: acidification potential; EP: eutrophication potential)**

**Figure 2 Main processes considered within the system boundary for the production system analyzed by the Crop.LCA tool (RM: Raw materials; O: oil; F: fuel; LO: lubricating oil; M: machinery; Fert: fertilizer; Pest: pesticide; H: herbicide; S: seed).**

**Figure 3 Boxplot of global warming potential with a 100 year horizon (GWP) for the cropping systems (a, b) and for wheat cultivation (c, d) according to the functional units considered (ha of land and GJ of energy output) (Bold line: median, Dashed line: mean, box: 25% and 75% quantiles, ○: maximum values, ♦: minimum values) (CONV: conventional; NT: no-tillage; L: legume; RES: residue)**

**Figure 4 Boxplot of (a,b) cumulative energy demand (CED), (c,d) eutrophication potential (EP,) and (e, f) acidification potential (AP) for the cropping systems with the functional units considered (ha of land and GJ of energy output) (Bold line: median, Dashed line: mean, box: 25% and 75% quantiles, ○: maximum values, ♦: minimum values) (CONV: conventional; NT: no-tillage; L: legume; RES: residue)**

Figure 1

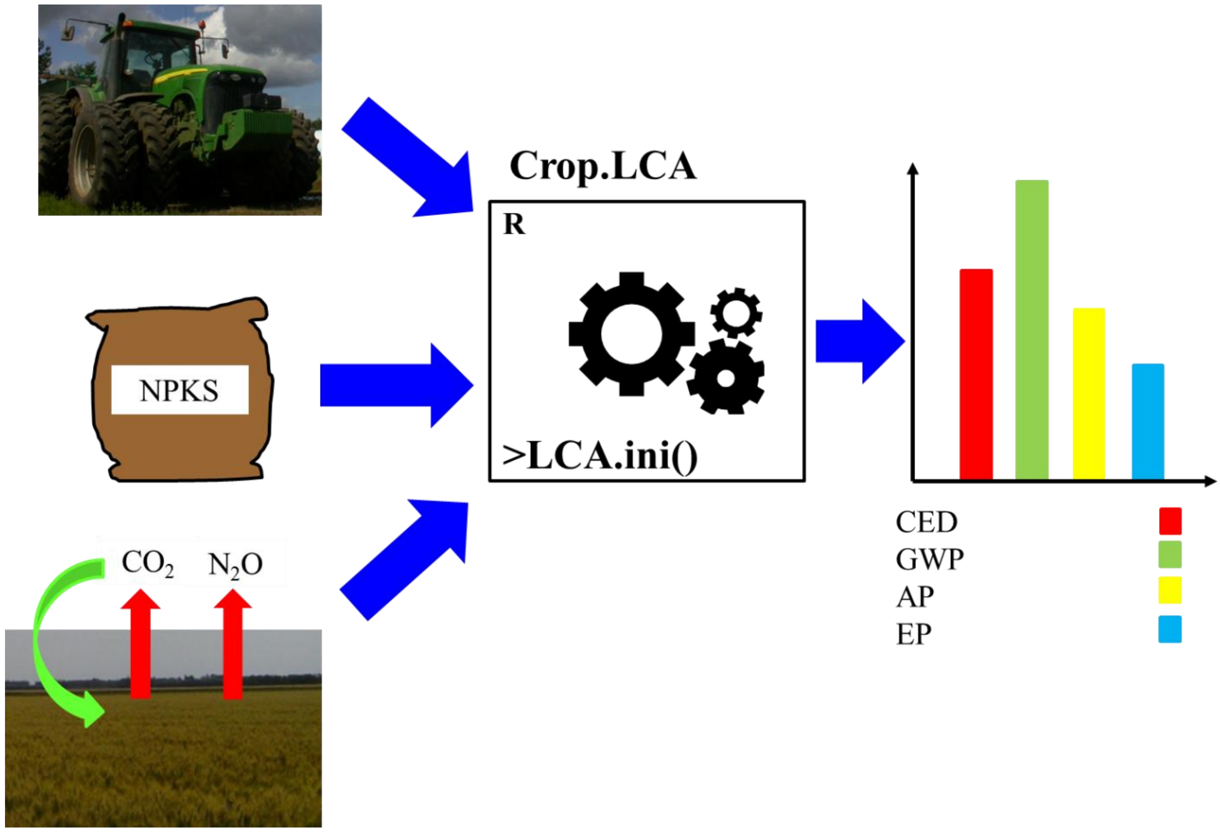

**Figure 2**

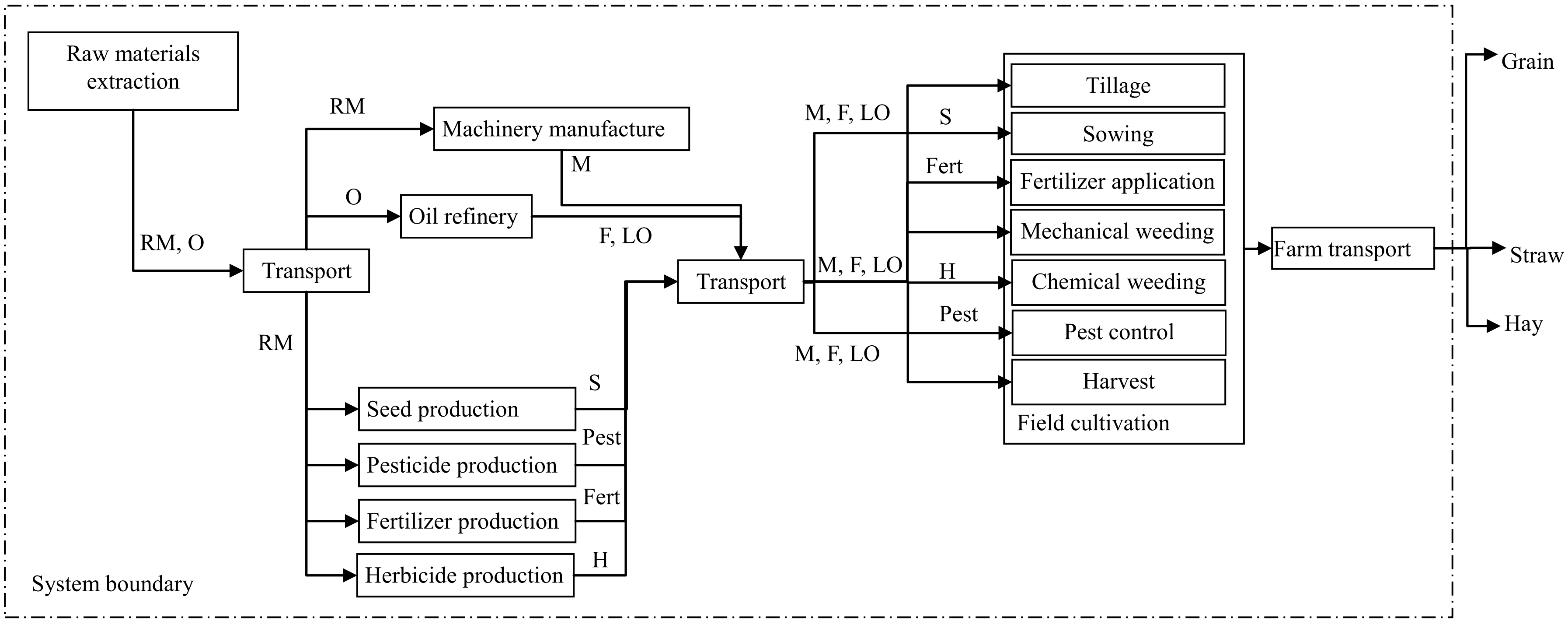
Raw materials extraction
RM, O
Transport
RM
Machinery manufacture
M
O
Oil refinery
F, LO
RM
Seed production
S
Pesticide production
Pest
Fertilizer production
Fert
Herbicide production
H
Transport
M, F, LO
M, F, LO
M, F, LO
S
Fert
H
Pest
Tillage
Sowing
Fertilizer application
Mechanical weeding
Chemical weeding
Pest control
Harvest
Field cultivation
Farm transport
Grain
Straw
Hay
System boundary

**Figure 3**

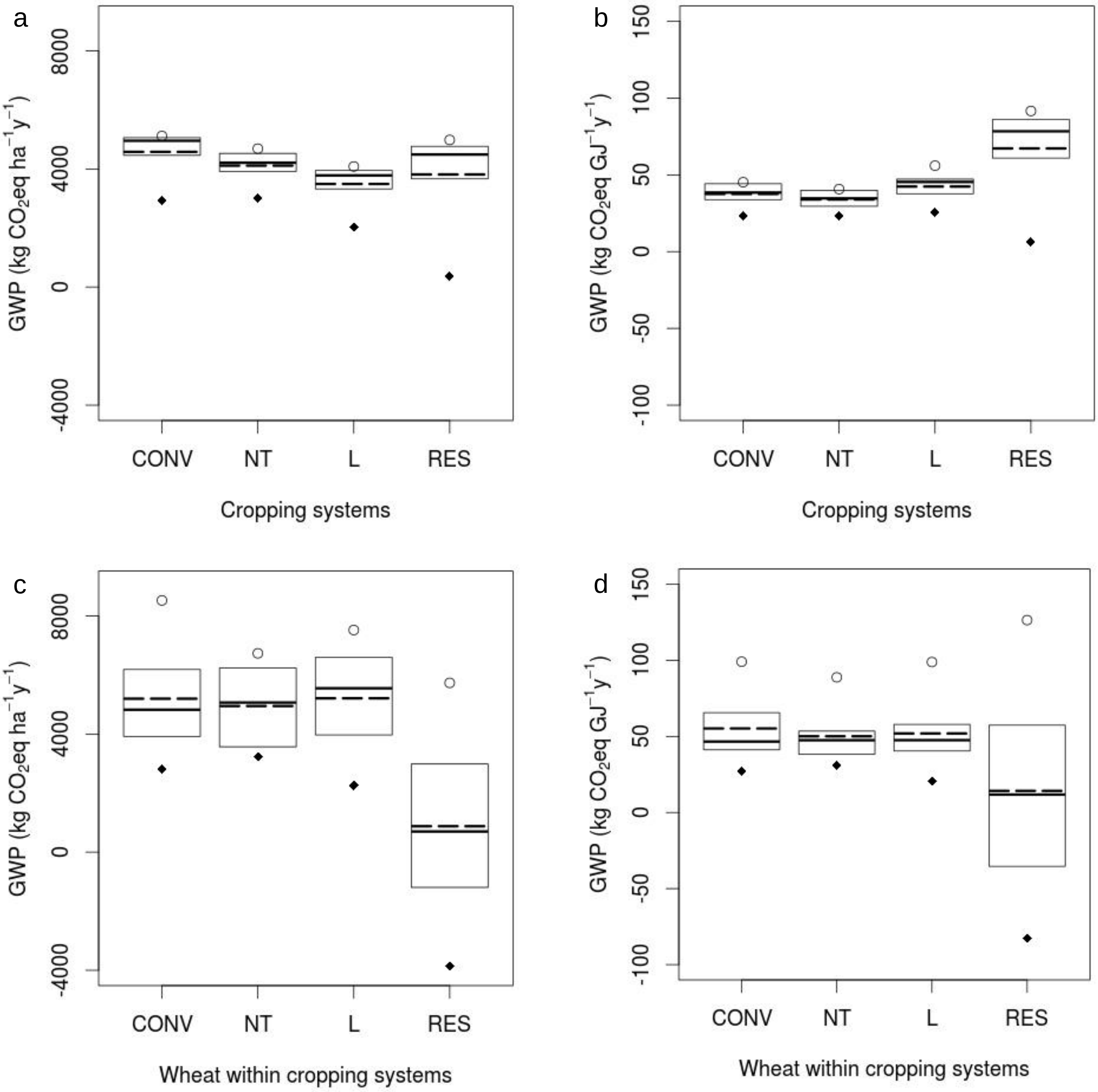
a
b
c
d
GWP (kg CO2eq ha-1 y-1)
GWP (kg CO2eq GJ-1 y-1)
8000
4000
0
-4000
150
100
50
0
-50
-100
CONV
NT
L
RES
Cropping systems
Wheat within cropping systems

**Figure 4**

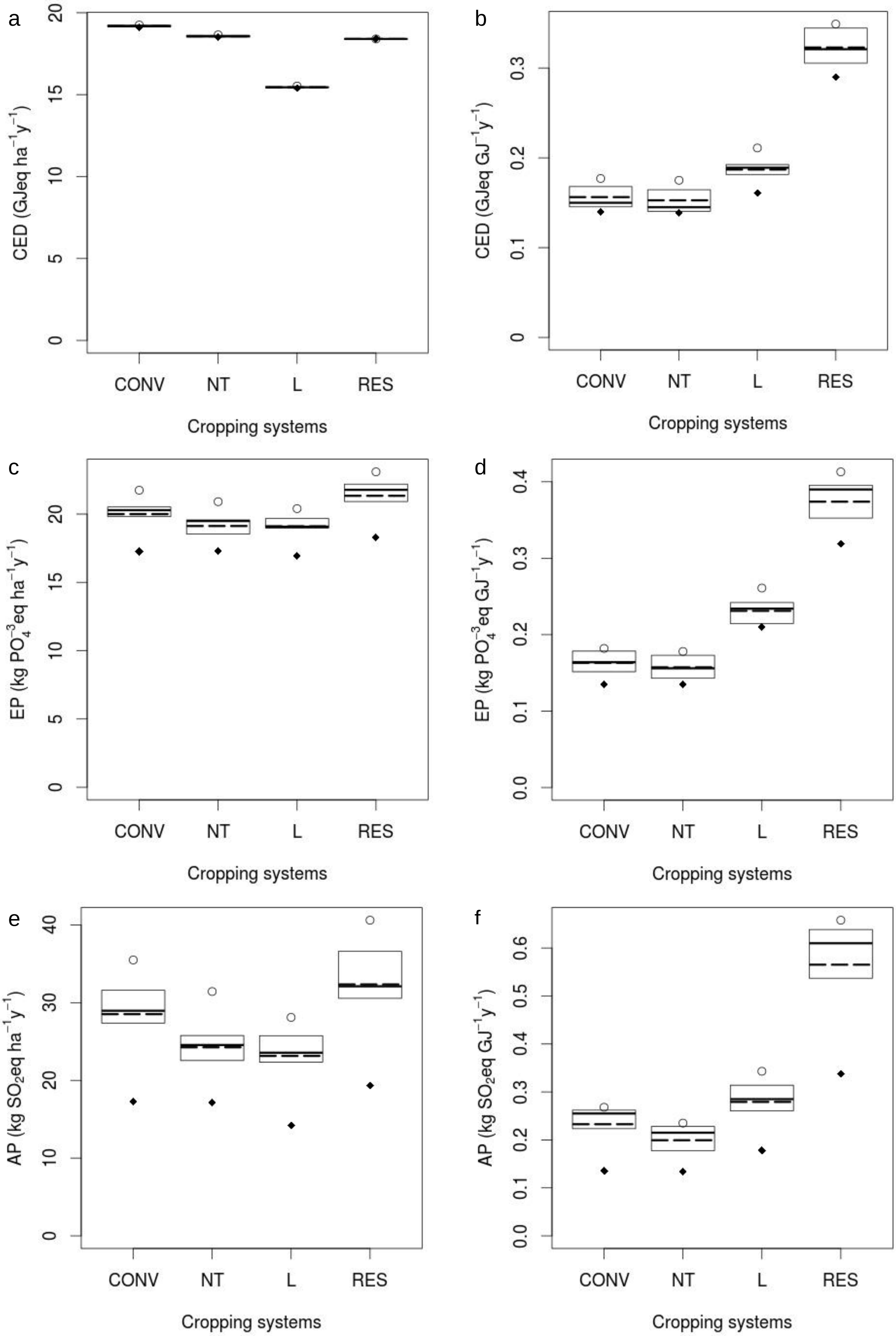
a
b
c
d
e
f
CED (GJeq ha$^{-1}$ y$^{-1}$)
CED (GJeq GJ$^{-1}$ y$^{-1}$)
EP (kg PO$_4^{-3}$eq ha$^{-1}$ y$^{-1}$)
EP (kg PO$_4^{-3}$eq GJ$^{-1}$ y$^{-1}$)
AP (kg SO$_2$eq ha$^{-1}$ y$^{-1}$)
AP (kg SO$_2$eq GJ$^{-1}$ y$^{-1}$)
CONV
NT
L
RES
Cropping systems

**Table 1**

**Table 1 Summary of characteristics of cropping systems considered in the scenario assessment (Note: Fertiliser cells in the Crop.LCA input file contain the amount of fertiliser applied and its nutrient concentration; further details are given in the Supplementary Material. Bold text indicates differences among systems)**

| Cropping System | | CONV | NT | L | RES |
|---|---|---|---|---|---|
| Name in the supplementary material | | 1 | 2 | 3 | 4 |
| Crop sequence[a] | | Maize-spring wheat-canola-spring barley | maize-spring wheat-canola-spring barley | **Faba bean-spring wheat-canola-spring barley** | maize-spring wheat-canola-spring barley |
| Tillage | | Harrowing and disk harrowing | **No tillage** | Harrowing and disk harrowing | Harrowing and disk harrowing |
| Fertiliser[b] | Year 1 | 180 kg $ha^{-1}$ NPKS<br>112 kg $ha^{-1}$ Urea | 180 kg $ha^{-1}$ NPKS<br>112 kg $ha^{-1}$ Urea | **0 kg $ha^{-1}$ NPKS**<br>**0 kg $ha^{-1}$ Urea** | 180 kg $ha^{-1}$ NPKS<br>112 kg $ha^{-1}$ Urea |
| | Year 2 | 213 kg $ha^{-1}$ NP | 213 kg $ha^{-1}$ NP | **106 kg $ha^{-1}$ NP** | 213 kg $ha^{-1}$ NP |
| | Year 3 | 317 kg $ha^{-1}$ Urea | 317 kg $ha^{-1}$ Urea | 317 kg $ha^{-1}$ Urea | 317 kg $ha^{-1}$ Urea |
| | Year 4 | 212 kg $ha^{-1}$ Urea | 212 kg $ha^{-1}$ Urea | 212 kg $ha^{-1}$ Urea | 212 kg $ha^{-1}$ Urea |
| Pesticide treatment number per year | | **1.5** | **2.5** | **1** | **1.5** |
| Residue management | | Straw and stover collected | Straw & stover collected | Straw and stover collected | **Straw and stover left on the field** |

[a] maize (*Zea mays* L.), spring wheat (*Triticum aestivum* L.), canola (*Brassica napus* L.), spring barley (*Hordeum vulgare* L.), and faba bean (*Vicia Faba* var. *minor* L.)

[b]Nutrient content: NPKS 35-25-10-10, NP 43-10, Urea 46

**Table 2**

**Table 2 Comparison of several characteristics of the LCA tools**

| Tool | AgBalance | Cranfield LCA tool | Crop.LCA | EU Carbon calculator | eVerdEE | FEAT model | LCAcommons | LCAD | SALCA | ULICEES |
|---|---|---|---|---|---|---|---|---|---|---|
| Impact category assessed | Several | Several | Several | GWP | Several | Several | Several | Several | Several | GWP |
| Modular | No | No | Yes | Yes | No | No | No | No | Yes | Yes |
| Adaptable[a] | No | No | Yes | Yes | No | Yes | Yes | No | No | No |
| Copyright issues | Available after purchase | Free | Free | Free | Free | Free | Free | Not available | Authors mentioned and agreement signed | By citing authors |
| Crop assessed | Several | Several | Several | Several | Several | Several | Several | bioenergy crops | Several | Several |
| Geographical area | W[b] | UK | W[b], currently focused on North America | Europe | W[b] | W[b] | North America | W[b] | Mostly focused on Europe | Mostly focused on North America |
| Availability | Available after purchase | Online | Online | Online | Online | Online | Online | Not available | On written request | On request |
| Code available | No | No | Yes | Yes | No | Yes | No | No | No | No |
| Multiapproach for cropping systems[c] | No | No | Yes | No | No | No | No | No | Yes | No |
| Does the tool allow for more than one input method for soil-borne emissions?[d] | No | No | Yes | No | No | No | No | No | No | No |
| References | BASF 2015 | Williams et al., 2010 | Current publication | Tuomisto et al., 2015 | Porta et al., 2008 | Camargo et al., 2013 | USDA 2015 | Styles et al., 2014, 2015 | Nemecek et al. 2010; Teuscher et al., 2014 | Vergé et al., 2012 |

[a]adaptable: Yes: the code of the tool and the data sources are available to the user for possible modifications which can be easily carried out, No: the code of the tool and the data sources are not available to the user for possible modifications which cannot be easily carried out.

[b]W: Worldwide

[c]multi-approach: Yes: individual crops and entire cropping systems can be considered at the same time; No: individual crops and entire cropping systems cannot be considered at the same time

[d]input method, in this context, refers to the methodology used to compute and estimate soil borne emissions

**Cranfield University**

**CERES Research Repository** **https://dspace.lib.cranfield.ac.uk/**

School of Water, Energy and Environment (SWEE) Staff publications (SWEE)

# Development of Crop.LCA, an adaptable screening life cycle assessment tool for agricultural systems: a Canadian scenario assessment

Goglio, Pietro

2017-06-22

Attribution-NonCommercial-NoDerivatives 4.0 International

Pietro Goglio, Ward N. Smith, Devon E. Worth, et al., Development of Crop.LCA, an adaptable screening life cycle assessment tool for agricultural systems: A Canadian scenario assessment, Journal of Cleaner Production, Vol. 172, 20 January 2018, pp. 3770-3780

http://dx.doi.org/10.1016/j.jclepro.2017.06.175

*Downloaded from CERES Research Repository, Cranfield University*