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6 2     **Development of Crop.LCA, an adaptable screening life cycle**  
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4 22 **Abstract**

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6 23 There is an increasing demand for sustainable agricultural production as part of the transition  
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8 24 towards a globally sustainable economy. To quantify impacts of agricultural systems on the  
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10 25 environment, life cycle assessment (LCA) is ideal because of its holistic approach. Many tools  
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12 26 have been developed to conduct LCAs in agriculture, but they are not publicly available, not  
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14 27 open-source, and have a limited scope. Here, a new adaptable open-source tool (Crop.LCA) for  
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16 28 carrying out LCA of cropping systems is presented and tested in an evaluation study with a  
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18 29 scenario assessment of 4 cropping systems using an agroecosystem model (DNDC) to predict  
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20 30 soil GHG emissions. The functional units used are hectares (ha) of land and gigajoules (GJ) of  
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22 31 harvested energy output, and 4 impact categories were evaluated: cumulative energy demand  
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24 32 (CED), 100-year global warming potential (GWP), eutrophication and acidification potential.  
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26 33 DNDC was used to simulate 28 years of cropping system dynamics, and the results were used as  
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28 34 input in Crop.LCA. Data were aggregated for each 4-year rotation and statistically analysed.  
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30 35 Introduction of legumes into the cropping system reduced CED by 6%, GWP by 23%, and  
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32 36 acidification by 19% per ha. These results highlight the ability of Crop.LCA to capture cropping  
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34 37 system characteristics in LCA, and the tool constitutes a step forward in increasing the accuracy  
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36 38 of LCA of cropping systems as required for bio-economy system assessments. Furthermore, the  
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38 39 tool is open-source, highly transparent and has the necessary flexibility to assess agricultural  
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57 51 **Keywords:** LCA, cropping systems, tool, scenario assessment, agriculture, open-source  
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# 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 (Huisingsh 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

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84 general purposes including the agricultural sector. However they were not specifically designed  
85 to assess agricultural systems, and they do not readily consider effects of crop management on  
86 soil emissions (Ciroth, 2007; GABI, 2016; SimaPro 8.3, 2016). Thus, researchers and the private  
87 sector have developed several tools for agricultural LCA (BASF, 2015; Nemecek et al., 2015;  
88 Tuomisto et al., 2015). For instance, SALCA (Swiss Agricultural Life Cycle Assessment) was  
89 developed by Agroscope to assess agricultural systems mainly in Central Europe (Nemecek et  
90 al., 2015). AgBalance is another tool developed to carry out LCA of agricultural systems.  
91 However, the user cannot access or modify the code of either tool. In addition AgBalance,  
92 which was conceived for the sustainability assessment of agriculture, must be purchased by the  
93 user (BASF, 2015; Nemecek et al., 2010; Teuscher et al., 2014). In contrast, other tools, such as  
94 the European Union (EU) Carbon Calculator and ULICEES, were developed to compute carbon  
95 (C) footprints (Tuomisto et al., 2015; Vergé et al., 2012), while the FEAT model also included  
96 energy consumption (Camargo et al., 2013). Porta et al. (2008) developed eVerdEE, a simplified  
97 tool for environmental product declarations in the agricultural sector. Similarly, the Cranfield  
98 LCA tool was developed to assess agricultural systems under United Kingdom (UK) conditions  
99 using Microsoft® Excel (Williams et al., 2010), while the LCAD tool was specifically designed  
100 to assess anaerobic digestion systems (Styles et al., 2014, 2015). LCAcommons is both a set of  
101 tools and life cycle inventories (LCI) developed for different production processes, including  
102 agricultural products, by several United States (US) governmental institutions (USDA, 2015).  
103 The existing LCA tools developed to assess agriculture are either simple tools, not publicly  
104 available, not modular or not open-source, which is considered advantageous for the LCA  
105 community (Ciroth, 2007). In this study, a new adaptable open-source tool (Crop.LCA) to carry  
106 out screening LCA of cropping systems is i) presented, ii) tested in an evaluation study  
107 consisting of a scenario assessment of 4 cropping systems using an agroecosystem model to  
108 predict soil emissions (i.e., CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub> and NH<sub>3</sub> volatilisation), and iii) used to compute the  
109 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<sub>2</sub>, biogenic CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, CO, NH<sub>3</sub>, NO<sub>2</sub>, SO<sub>2</sub>, non-methane volatile organic compounds, particulate matter, SF<sub>6</sub>, nitrate leaching, PO<sub>4</sub><sup>-3</sup>, 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<sub>2</sub>; CH<sub>4</sub> and

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4 140 N<sub>2</sub>O; machinery use, production and repair; fertiliser production and transport). If the results of  
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6 141 soil CO<sub>2</sub> emissions are negative, it means that soil C sequestration occurred.  
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## 9 142 **2.2. System boundary**

10 143 The system boundary considered by Crop.LCA includes the agricultural phase, along with soil  
11 144 GHG emissions, NH<sub>3</sub> volatilisation, NO<sub>3</sub><sup>-</sup> leaching and all upstream processes, including  
12 145 machinery production, transport, maintenance and repairs, fertiliser, pesticide and seed  
13 146 production and transport (Fig. 2). The downstream limit is the transport of the agricultural  
14 147 products (e.g. grain, hay or silage) to the farm centre (i.e., location of the main farm facilities,  
15 148 including barns, silage pits and machinery storage facilities) (Fig. 2). Drying, silage pit filling,  
16 149 and hay storage are excluded. In agreement with previous research and ISO standards, all  
17 150 upstream processes from raw material extraction up to the regional storehouse (i.e. a building of  
18 151 the local suppliers of agricultural inputs) are included (Audsley et al., 1997; Brentrup et al.,  
19 152 2004; ISO, 2006a, 2006b, 2013). Transport processes from raw material extraction to the farm  
20 153 centre were included within the system boundary.  
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## 31 154 **2.3. Data sources and treatment for the life cycle inventory**

32 155 Field data are used as inputs to Crop.LCA. All upstream processes used emission factors derived  
33 156 from available literature. For instance, data for the production of fuel, electricity, steel, and  
34 157 rubber in Crop.LCA were derived from GHGenius ((S&T)2, 2014). GHGenius is a tool  
35 158 developed to account for environmental impacts of different vehicles in Canadian and US  
36 159 conditions with a cradle-to-wheel approach ((S&T)2, 2014). The data currently available in  
37 160 Crop.LCA for both background and foreground processes are relevant to North American  
38 161 conditions; however, data from other sources can be integrated in Crop.LCA by changing the  
39 162 corresponding input files available on the bitbucket platform  
40 163 (<https://bitbucket.org/croplcateam/crop.lca>), following the user manual and by collecting site-  
41 164 specific data for background processes. Data for seed, fertiliser and pesticide production were  
42 165 taken from other data sources (Bhatty et al., 1979; Boehmel et al., 2008; Brentrup et al., 2004;  
43 166 Ceccon et al., 2002; Gasol et al., 2012; Goglio et al., 2012; Haciseferoğulları et al., 2003;  
44 167 (S&T)2, 2014). Urea and ammonia production data were derived from several data sources  
45 168 associated with North American conditions (Brentrup et al., 2004; Sheehan et al., 1998; (S&T)2,  
46 169 2014). Data for inputs used during cultivation were treated as described below.  
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### 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)<sup>2</sup>, 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)<sup>2</sup>, 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<sub>2</sub>, CH<sub>4</sub> emissions, N<sub>2</sub>O) are read as inputs and included in computation of the LCI. In particular, Crop.LCA sums up GWP from all sources including CO<sub>2</sub> from soil C changes and computes soil CO<sub>2</sub> emissions in agreement with currently available LCA methods (Goglio et al., 2015). Crop.LCA predicts indirect N<sub>2</sub>O 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



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4 228 files can be edited in a spreadsheet following the user manual. All input files are in comma  
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6 229 separated value (.csv) format. For background processes, Crop.LCA uses data from literature  
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8 230 and other databases (e.g., GHGenius)(S&T)2, 2014). Other modules in Crop.LCA have also been  
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10 231 designed to compute GWP, EP, and AP.

### 14 232 **3. Evaluation study**

#### 17 233 **3.1. Case study scenario assessment**

18 234 A case study was used to validate Crop.LCA, based on a scenario assessment of 4 cropping  
19 235 systems studied in a field experiment described by Glenn et al. (2010, 2011, 2012) and Maas et  
20 236 al. (2013), located at the Glenlea Research Station (49.64°N, 97.16°W; 235 m a.s.l.), on the Red  
21 237 River plain (<2% slope) near Winnipeg, Manitoba, Canada. Mean soil organic C content (0–  
22 238 0.2 m) at the beginning of the study was approximately 3.2%. Particle size distribution was 60%  
23 239 clay, 35% silt, and 5% sand. The impact categories and system boundary considered in the LCA  
24 240 are the same as those in Crop.LCA. The functional units used are ha of land and GJ of gross  
25 241 energy output.

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27 243 The conventional (CONV) cropping system (Table 1) has a crop management system similar to  
28 244 that of the annual cropping system described by Glenn et al. (2010, 2011, 2012). The CONV, no-  
29 245 tillage (NT), and residue (RES) systems include the same crop sequence with no cover crops  
30 246 (maize-spring wheat (*Triticum aestivum* L.)-canola (*Brassica napus* L.)-spring barley (*Hordeum*  
31 247 *vulgare* L.)), while in the legume (L) system, faba bean (*Vicia faba* var. *minor* L.) replaces maize  
32 248 (Table 1). In the RES system, straw and maize stover are left in the field, unlike in the other  
33 249 systems (Table 1). Full details can be found in the supplementary material.

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35 251 For the scenario assessment, a Canadian version (DNDC v.CAN) (Grant et al., 2016; Kröbel et  
36 252 al., 2011; Smith et al., 2013) of the DNDC (Denitrification and Decomposition) model (Li et al.,  
37 253 1992, 1994) was run using 28 years (1985–2012) of climate data (i.e., daily max. and min.  
38 254 temperature, precipitation, global solar radiation, humidity and wind speed). DNDC estimates of  
39 255 GHG emissions, grain yields, crop residues, and nitrate and ammonia losses were used as inputs  
40 256 for the Crop.LCA tool. Yearly data (1<sup>st</sup> Jan –31<sup>st</sup> Dec) for each impact category were aggregated

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4 257 to compute a mean impact for each 4-year rotation (e.g., 1985–1988, 1989–1992) of the cropping  
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6 258 systems to have 7 sample elements for statistical analysis. Yearly data were used, as all of the  
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8 259 crops have a similar life cycle (~150-day growth, spring sown with fall harvest). Only 2% of the  
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10 260 harvested area of crops in the study region is sown in autumn (CANSIM, 2016). However,  
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12 261 Crop.LCA can compute impacts for different timeframes when necessary (e.g. harvest of the  
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14 262 previous crop to harvest of the given crop). The impacts for spring wheat were also calculated  
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16 263 separately, since it is a major crop in the region (CANSIM, 2016). The harvested energy output  
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18 264 (GJ) is computed from yields and the upper heating value (or gross energy) of the harvested  
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20 265 biomass.

### 21 266 **3.2. DNDC model and simulations**

23 267 DNDC was originally developed to estimate N<sub>2</sub>O emissions (Li et al., 1992), but it has been  
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25 268 expanded to simulate soil C and nitrogen (N) dynamics and CO<sub>2</sub> emissions (Li et al., 1994). The  
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27 269 model has been developed and tested for many soils, climates, and cropping systems. Several  
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29 270 regional versions are available on the Global Research Alliance Modelling Platform  
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31 271 (<http://gramp.org.uk/models/family/2>). DNDC (DNDCv.CAN) was first run for 10 years to  
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33 272 stabilise C and N pools before estimating soil GHG emissions for each system. The climate data,  
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35 273 crop, and soil inputs for the simulations were obtained from Uzoma et al. (2015), who found  
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37 274 DNDC reasonably simulated soil temperature, soil water content, soil N, and N<sub>2</sub>O emissions for  
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39 275 annual cropping.

### 41 276 **3.3. Statistical analyses**

42 277 Statistical analyses were conducted with R to investigate whether i) the CED, GWP, AP, and EP  
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44 278 of the cropping systems and ii) the GWP of wheat, for both functional units (ha and GJ), were  
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46 279 statistically different. A Friedman test was first performed, followed by pair-wise non-parametric  
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48 280 comparisons, considering each 4-year rotation separately for the entire cropping system  
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50 281 assessment and each year of wheat cultivation separately (Siegel and Castellan, 1988). There  
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52 282 were thus 7 sample elements (i.e., 4-year rotation average) available for the statistical analyses,  
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54 283 while one value for each 4-year rotation was used to assess impacts of wheat cultivation.  
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56 284 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 ( $3740 \text{ kg CO}_2\text{eq ha}^{-1} \text{ y}^{-1}$ , Fig. 3a), 23% less than that in the CONV system. In contrast, wheat in the RES system had the lowest mean GWP per ha ( $1670 \text{ kg CO}_2\text{eq ha}^{-1} \text{ y}^{-1}$ , 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  $38 \text{ kg CO}_2 \text{ eq GJ}^{-1}\text{y}^{-1}$ , 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  $\text{CO}_2$  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  $\text{CO}_2$  absorption of the crop from the atmosphere and the consequent increase in soil C from retained residues. The contribution of direct  $\text{N}_2\text{O}$  emissions to GWP averaged  $171\%$  among the systems while the mean contribution of the indirect  $\text{N}_2\text{O}$  emissions to GWP was smaller ( $12\%$ ).

The CONV system had the highest mean CED per ha ( $19.2 \text{ GJ ha}^{-1} \text{ y}^{-1}$ ) (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 ( $0.153 \text{ GJ GJ}^{-1} \text{ y}^{-1}$ ),  $2.4\%$  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 ( $19.1 \text{ kg of PO}_4^{-3}\text{eq ha}^{-1} \text{ y}^{-1}$ ),  $4.5\%$  less than that in the CONV system. For EP per GJ, the NT system had the lowest EP ( $0.157 \text{ kg of PO}_4^{-3}\text{eq GJ}^{-1} \text{ y}^{-1}$ , Fig. 4d),  $3.5\%$  less than that in the CONV system. The RES system had the highest mean AP per ha ( $32.3 \text{ kg SO}_2\text{eq ha}^{-1} \text{ y}^{-1}$ , 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 ( $0.565 \text{ kg SO}_2\text{eq GJ}^{-1} \text{ y}^{-1}$ , Fig. 4f),  $68.0\%$  higher than that in the CONV system, while the NT system had the lowest AP ( $0.199 \text{ kg of SO}_2\text{eq GJ}^{-1} \text{ y}^{-1}$ ),  $14.3\%$  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 ( $13\text{-}19\text{ GJ ha}^{-1}\text{ y}^{-1}$ ) were close to the range of values reported by Pelletier et al. (2008) for organic and conventional wheat, maize, and canola ( $1.9\text{-}17\text{ GJ ha}^{-1}\text{ y}^{-1}$ ) on the basis of average Canadian conditions for cultivation and using statistical data. CED per GJ ( $0.15\text{-}0.32\text{ GJ GJ}^{-1}$ ) agreed with results obtained by Goglio et al. (2014) ( $0.25\text{-}0.39\text{ GJ GJ}^{-1}$ ) 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  $\text{N}_2\text{O}$  and soil  $\text{CO}_2$  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  $\text{N}_2\text{O}$  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  $\text{N}_2\text{O}$

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4 345 emissions to overall GWP in a cropping system containing wheat and barley in eastern  
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10 348 The EP results per ha (19-21 kg PO<sub>4</sub><sup>3-</sup>eq ha<sup>-1</sup>) are in line with those of other LCA studies for  
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12 349 similar crops (e.g., wheat and maize) (17-58 kg PO<sub>4</sub><sup>3-</sup>eq ha<sup>-1</sup>) (Bacchetti et al., 2015; Goglio et  
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14 350 al., 2012) under different soil and climate conditions. The EP for the entire cropping system was  
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16 351 at least 24% larger than those obtained for maize cultivation at several locations in the US maize  
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18 352 belt (Kim et al., 2009) using the DAYCENT model, most likely due to different methods used to  
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20 353 estimate nitrate leaching.  
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23 355 The AP results per ha lie within the range of those reported by Kim et al. (2009) for US maize  
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25 356 production using DAYCENT (22-53 kg SO<sub>2</sub>eq ha<sup>-1</sup> y<sup>-1</sup>). However, AP per ha in the current study  
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27 357 was at least 5.4 times as large as the AP reported by Goglio et al. (2012), who performed an LCA  
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29 358 of cropping systems, including maize and wheat, in Mediterranean conditions. In contrast, AP  
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31 359 per ha was >55% lower than the AP reported by Bacchetti et al. (2015) for maize cultivation in  
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33 360 northern Italy. The results obtained in this study demonstrate the strong influence that crop  
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35 361 selection can have on the overall performance of cropping systems (Camargo et al., 2013; Gan et  
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37 362 al., 2011; MacWilliam et al., 2014; Nemecek et al., 2015), highlighting the importance of  
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39 363 designing sustainable cropping systems within the context of a bio-economy.  
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#### 41 364 42 365 **4.2. Comparison with other LCA tools**

43 366 Open-source LCA tools are highly sought within the LCA community (Ciroth, 2007) because  
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45 367 they increase transparency, which hastens development. Having full access to the source code,  
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47 368 the LCA user can modify functions as required, which was previously suggested as advantageous  
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49 369 for the openLCA tool (Ciroth, 2007). The availability of the source code gives more flexibility,  
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51 370 which is necessary to account for variability, which is common in agricultural systems  
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53 371 (Börjesson and Tufvesson, 2011). Among the tools assessed, only Crop.LCA and the FEAT  
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55 372 model are open-source (Table 2). However, the FEAT model is not modular, does not allow a  
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57 373 multi-approach assessment, where a single crop and a cropping system are assessed at the same  
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59 374 time and does not incorporate multiple methods to account for soil emissions (Camargo et al.,  
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61 375 2013).  
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6 377 Crop.LCA was developed with a modular framework, which makes it easy to use from a  
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8 378 programming standpoint, as with SALCA and the EU Carbon Calculator (Nemecek et al., 2010,  
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10 379 2015; Teuscher et al., 2014; Tuomisto et al., 2015) (Table 2). The modular framework also  
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12 380 allows exclusion or inclusion of specific processes (e.g., machinery production, fertiliser  
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14 381 application) by enabling and disabling the corresponding functions in the source code. Crop.LCA  
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16 382 can therefore be rapidly adapted to different goals and scopes of agricultural LCA (Teuscher et  
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18 383 al., 2014). The Crop.LCA tool can assess entire cropping systems over several years as a single  
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20 384 entity, or individual crops, which is considered important (Brankatschk and Finkbeiner, 2015;  
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22 385 Knudsen et al., 2014; Nemecek et al., 2015). In contrast with Crop.LCA, SALCA does not  
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24 386 account for more than one input method to account for soil emissions and is not adaptable, while  
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26 387 the EU Carbon Calculator considers only GWP, excludes other impact categories and does not  
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28 388 allow multiple methods to be used for soil emissions (Table 2) (Tuomisto et al., 2015).

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32 390 Crop.LCA is publicly available online, can be run in R with few commands, and uses .csv files.  
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34 391 The user-friendly framework is similar to that of the SALCA and LCAD tools, the FEAT model  
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36 392 and the EU Carbon Calculator, which are Excel-based macros. It is also similar to the eVerDEE  
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38 393 tool, which includes a graphical user interface (Table 2) (Camargo et al., 2013; Nemecek et al.,  
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40 394 2010; Porta et al., 2008; Styles et al., 2014, 2015; Teuscher et al., 2014; Tuomisto et al., 2015).

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44 396 Unlike some previous tools developed for LCA or C footprint assessment, Crop.LCA includes  
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46 397 other impact categories besides GWP, such as EP and AP (Camargo et al., 2013; Dyer and  
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48 398 Desjardins, 2003; Tuomisto et al., 2015; Vergé et al., 2012) (Table 2). Furthermore, it was  
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50 399 developed in compliance with ISO standards (ISO, 2006a, 2006b, 2013), focuses on crop  
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52 400 management and applies characterization factors from the IPCC 5<sup>th</sup> Assessment Report (Myhre  
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54 401 et al., 2013).

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58 403 Crop.LCA is a comprehensive tool which can characterise field operations, depending on the  
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60 404 type of machinery used, its weight and power. It shares these features with SALCA, but uses a  
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62 405 more complex approach than eVerDEE (Nemecek et al., 2010; Porta et al., 2008; Teuscher et al.,  
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64 406 2014). Crop.LCA has the potential to be adapted by the user to carry out LCA of a wide range of  
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4 407 crops, including catch crops, cover crops, and other temperate and tropical crops. For this reason,  
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6 408 it can be used to assess bio-economic systems involving many products and production pathways  
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8 409 (Philp, 2015). The current version of Crop.LCA cannot represent as many crops as several other  
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10 410 tools (BASF, 2015; Camargo et al., 2013; Nemecek et al., 2010; Porta et al., 2008; Styles et al.,  
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12 411 2014, 2015; Teuscher et al., 2014) (Table 2); however, they contain other limitations when  
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14 412 compared with Crop.LCA. For instance, SALCA currently focuses on Swiss and central  
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16 413 European systems. Other models can be used worldwide, such as AgBalance, eVerdEE, the  
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18 414 FEAT model, and LCAD (BASF, 2015; Camargo et al., 2013; Porta et al., 2008; Styles et al.,  
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20 415 2014, 2015). Crop.LCA can also be integrated to carry out either spatialised or regional LCA.  
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23 417 One limitation of Crop.LCA is that it is based mostly on North American conditions (Table 2). In  
24  
25 418 addition like some other tools (USDA, 2015; Vergé et al., 2012), life cycle inventory analysis of  
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27 419 the background processes was not part of the original development objectives of Crop.LCA.  
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29 420 Thus, input data files for unit processes for background processes (e.g., the production of  
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31 421 fertilizers, pesticides, seeds), occurring outside North American conditions, are currently not  
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33 422 available and need to be prepared by the LCA practitioner using other software and databases  
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35 423 (e.g., SimaPro, (SimaPro 8.3, 2016)) to conduct site-specific assessments. However, being open-  
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37 424 source, users can select geographically specific input files (e.g. soils and impact factors) or use  
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39 425 empirical data. Furthermore, users can develop the code to include other impacts, processes, data  
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41 426 sources or features. Many calculation libraries are available in R, which offers the adaptability  
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43 427 needed for assessing new bio-economic systems and current systems in new ways.  
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#### 46 47 429 **4. Conclusion**

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49 430 Crop.LCA can capture the interactions of soil, climate and crop management for a variety of  
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51 431 cropping systems. The main strength of Crop.LCA is that it is transparent and open-source;  
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53 432 therefore, the code can be modified by the LCA practitioner as needed. The availability of the  
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55 433 source code provides more flexibility, which is necessary to account for variability in agricultural  
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57 434 systems. Crop.LCA can also be used for site-specific assessments, increasing the accuracy of  
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59 435 bio-economic assessments. The tool has the advantage of accounting for several substances,  
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436 allowing for the assessment of individual crops or cropping systems over several years. Further  
437 developments should include the introduction of new substances and impact categories.

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

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### 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

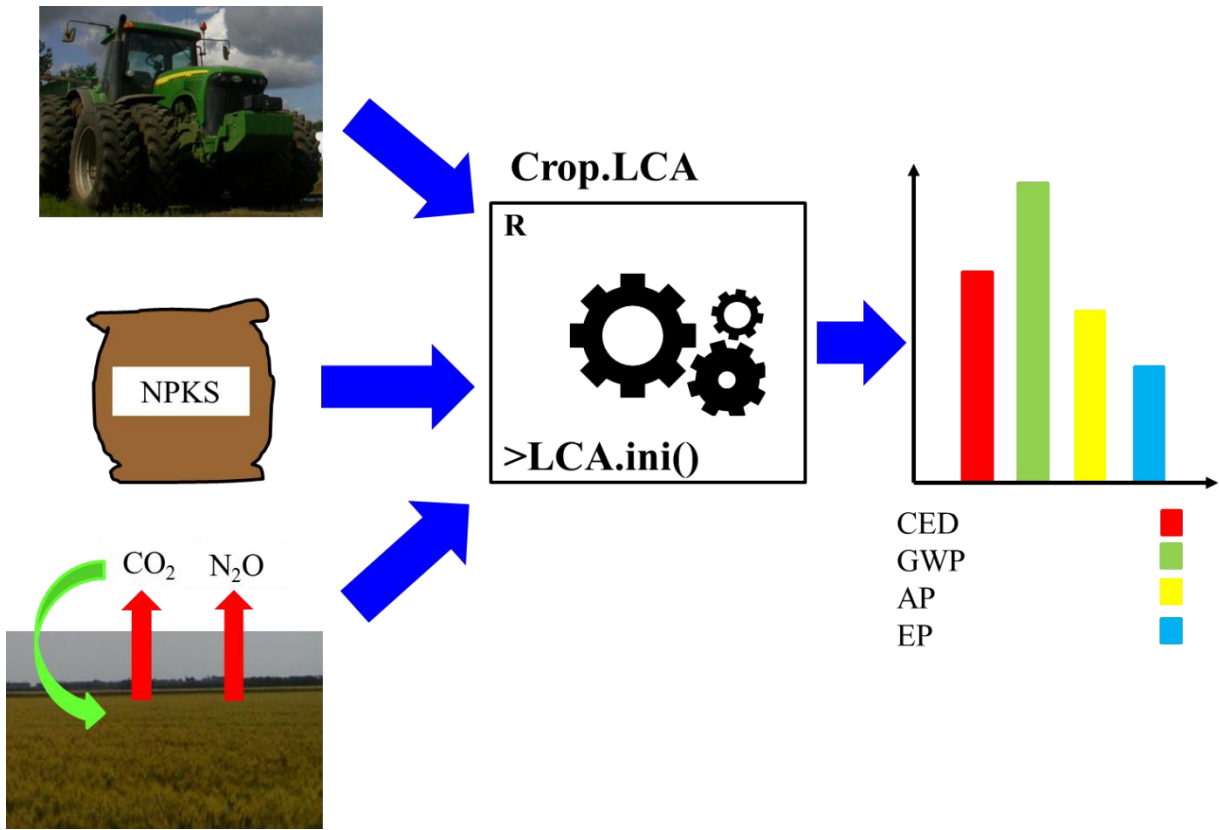


Figure 2

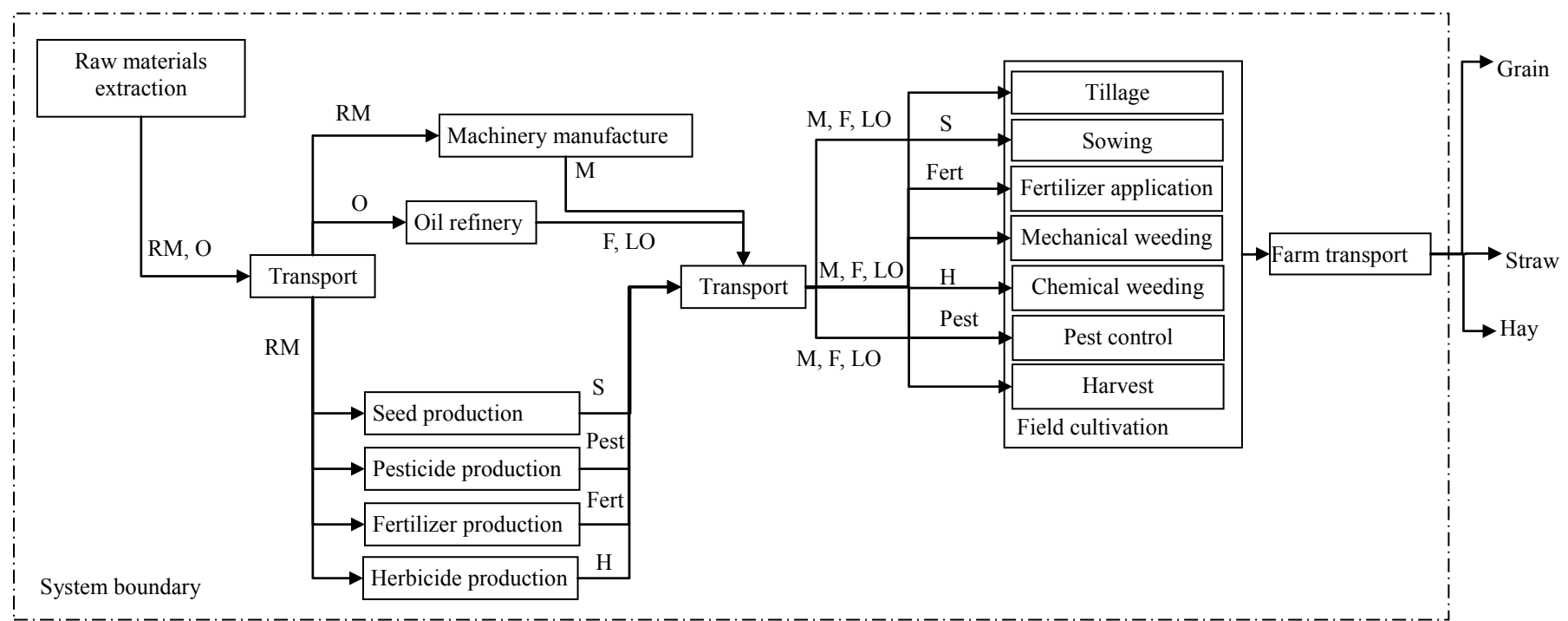


Figure 3

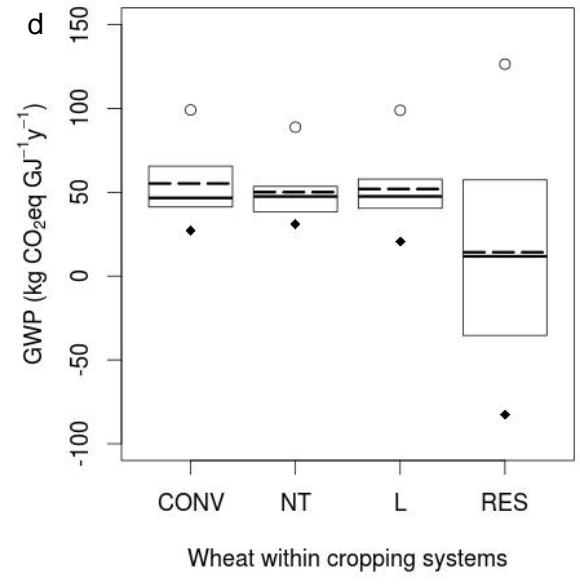
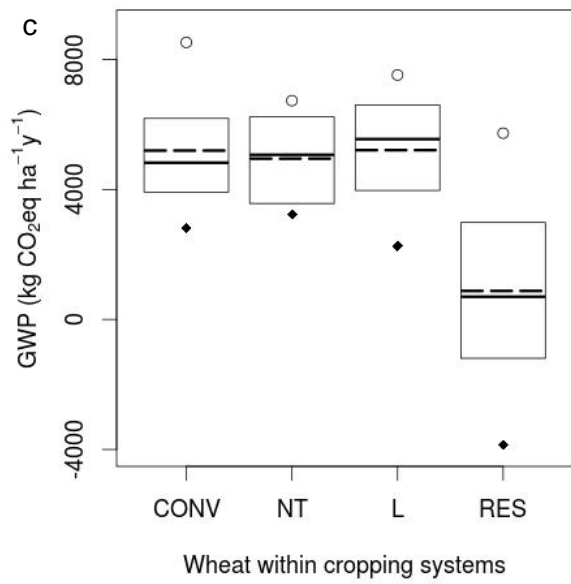
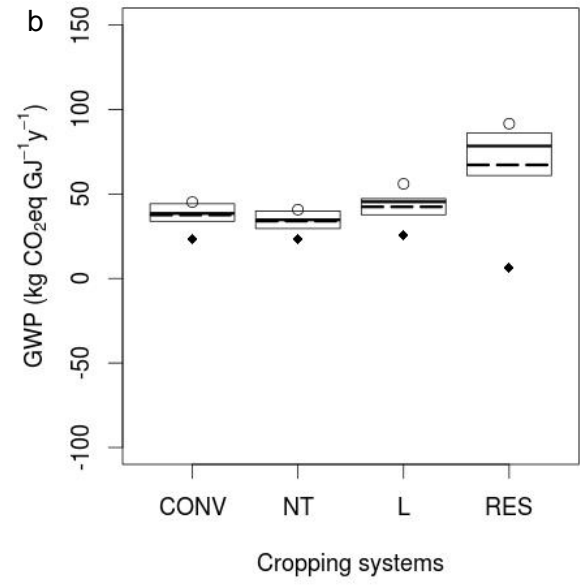
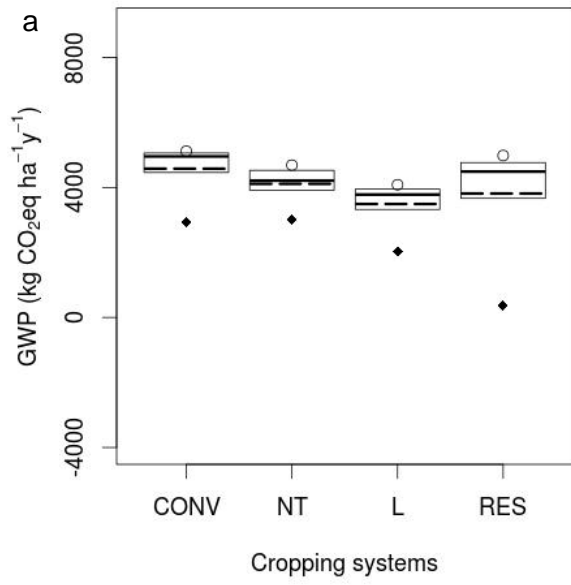
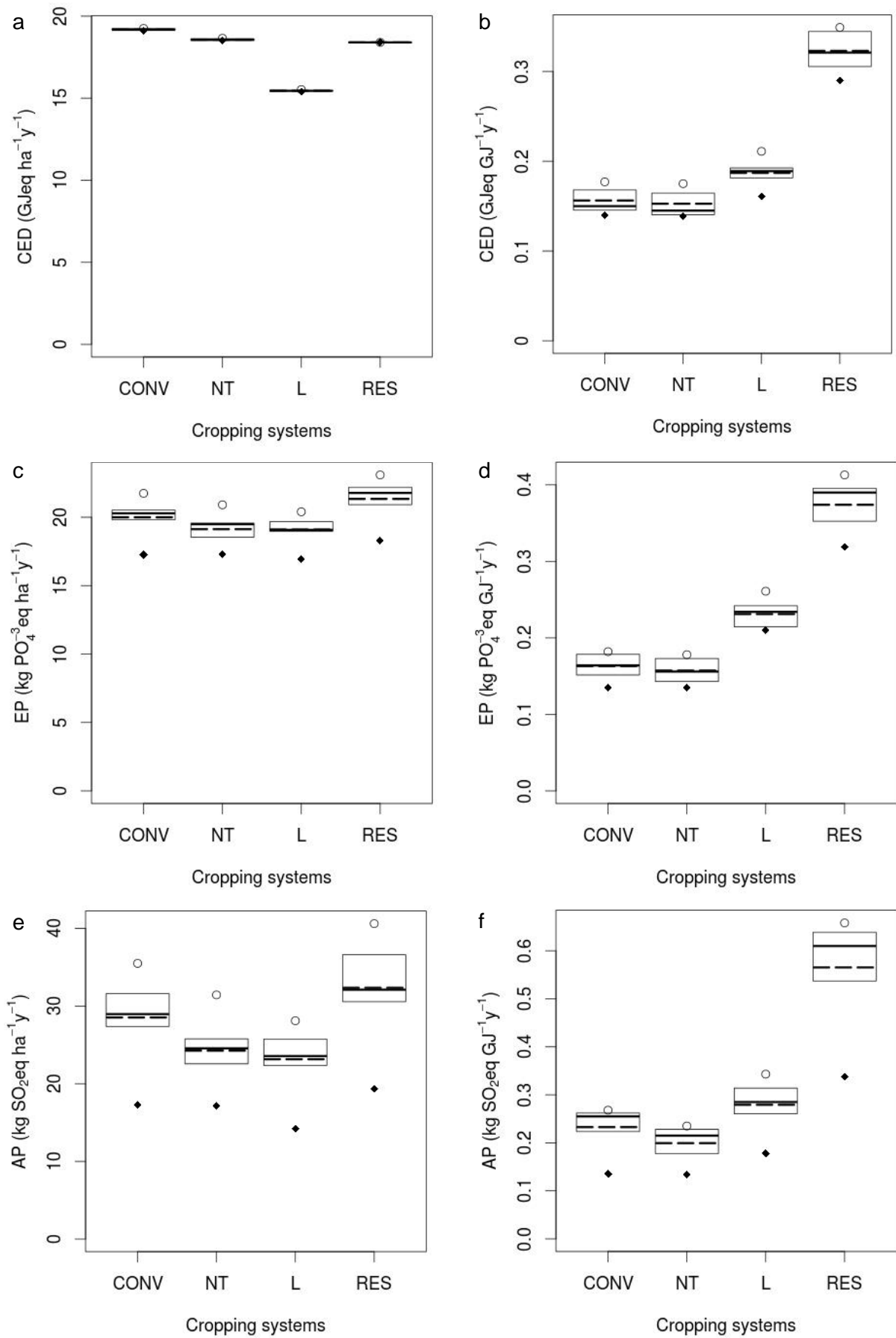


Figure 4



**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 <sup>a</sup>	Maize-spring wheat-canola-spring barley	maize-spring wheat-canola-spring barley	<b>Faba bean-spring wheat-canola-spring barley</b>	maize-spring wheat-canola-spring barley
Tillage	Harrowing and disk harrowing	<b>No tillage</b>	Harrowing and disk harrowing	Harrowing and disk harrowing
Fertiliser <sup>b</sup>				
Year 1	180 kg ha <sup>-1</sup> NPKS 112 kg ha <sup>-1</sup> Urea	180 kg ha <sup>-1</sup> NPKS 112 kg ha <sup>-1</sup> Urea	<b>0 kg ha<sup>-1</sup> NPKS</b> <b>0 kg ha<sup>-1</sup> Urea</b>	180 kg ha <sup>-1</sup> NPKS 112 kg ha <sup>-1</sup> Urea
Year 2	213 kg ha <sup>-1</sup> NP	213 kg ha <sup>-1</sup> NP	<b>106 kg ha<sup>-1</sup> NP</b>	213 kg ha <sup>-1</sup> NP
Year 3	317 kg ha <sup>-1</sup> Urea	317 kg ha <sup>-1</sup> Urea	317 kg ha <sup>-1</sup> Urea	317 kg ha <sup>-1</sup> Urea
Year 4	212 kg ha <sup>-1</sup> Urea	212 kg ha <sup>-1</sup> Urea	212 kg ha <sup>-1</sup> Urea	212 kg ha <sup>-1</sup> Urea
Pesticide treatment number per year	<b>1.5</b>	<b>2.5</b>	<b>1</b>	<b>1.5</b>
Residue management	Straw and stover collected	Straw & stover collected	Straw and stover collected	<b>Straw and stover left on the field</b>

<sup>a</sup> 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.)

<sup>b</sup>Nutrient content: NPKS 35-25-10-10, NP 43-10, Urea 46

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 <sup>a</sup>	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 <sup>b</sup>	UK	W <sup>b</sup> , currently focused on North America	Europe	W <sup>b</sup>	W <sup>b</sup>	North America	W <sup>b</sup>	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 <sup>c</sup>	No	No	Yes	No	No	No	No	No	Yes	No
Does the tool allow for more than one input method for soil-borne emissions? <sup>d</sup>	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

<sup>a</sup>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.

<sup>b</sup>W: Worldwide

<sup>c</sup>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

<sup>d</sup>input method, in this context, refers to the methodology used to compute and estimate soil borne emissions