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2 **Interactive life cycle assessment framework to evaluate agricultural**
3 **impacts and benchmark emission reduction credits from organic**
4 **management**

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14
15 **Abstract**

16 Growers who manage farming systems organically strive to maintain balanced
17 ecosystems for sustainable food production. We examined a life cycle assessment
18 framework to support an interactive evaluation and benchmarking of emission
19 reduction credits (ERC) from organically managed crop production. Open source Life
20 Cycle Analysis (LCA) software was used to streamline inventories for organic
21 farming. The inventories were built on hierarchical levels of inputs, land operations,
22 crops and crop rotation. The methodology was demonstrated by comparing: (1) only
23 carbon footprints of the baseline inventories and land operations, then (2) all
24 environmental impacts of organic potato production versus US conventional potato
25 production and other inventoried international potato production systems to highlight
26 effects of management differences. The footprints of inventoried land operations
27 showed trade-off effects between the size of equipment and the degree of plant
28 residue incorporation into soil, e.g. by shredding. Total impact and ecotoxicity
29 impacts per kg potato production were reduced approximately three orders of
30 magnitude on the US organic case study farm as compared to the inventoried US
31 average conventional production. The examined LCA supports the benchmarking of
32 ERC from organic management. It is, therefore, recommended to use the framework
33 in future case studies of organic farms and comparative LCA's.

- 1 Keywords
- 2 emission reduction credits (ERC), ecosystem services, EPA-TRACI, GWP,life cycle
- 3 assessment
- 4

1. INTRODUCTION

Intensification of agricultural production through conventional green revolution methods has undermined the capacity of agroecosystems to sustain production (Foley et al., 2005). While intensification of agriculture is meant to increase crop yields to meet growing global food demands, the intensification of tillage, fossil fuel use, and nutrient extraction increases emissions and environmental degradation (Foley et al., 2011). As a partial solution, organic management of cropping systems maintains ecosystem conditions (Altieri, 1999; Kohl et al., 2014; Zhang et al., 2007) and mitigates environmental impacts for more sustainable food production (Underwood et al., 2011) at the cost of marginal yield reductions (de Ponti et al., 2012; Ponisio et al., 2014). Our goal was to implement and test a framework for the evaluation of emission reductions comparing general agricultural inputs and organic management activities. In this paper, we define emission reduction credits (ERC) as the difference of ecological footprints between two agricultural inputs or systems.

According to the UN-FAO (2014) definition, organic farming uses agronomic, biological, and mechanical methods, as opposed to the synthetic chemicals of conventional agriculture. Organic farming relies on slow mechanisms to reduce emissions such as slow release of nutrients from organic fertilizers. Such slow mechanisms require interactive simulation for the assessment of the emissions on the long term. The assessment of conventional agriculture relies more on evaluation of synthetic inputs that are more readily available when applied to the soil. Impacts from synthetic inputs depend on their supply chains that are defined from industrial processes. Synthetic inputs such as inorganic fertilizers and pesticides are mainly produced from fossil fuels and petrochemicals (Miller and Spoolman, 2010). Life Cycle Assessment (LCA) allows the assessment of energy, fuel and material inputs (Woods et al., 2010). The application of LCA approaches is needed to evaluate agriculture's impacts within expanded boundaries considering both supply chains and farm-level data. LCA compares both global and local impacts of agricultural systems (Haas et al., 2000; Van der Werf and Petit, 2002). For the last decade, agricultural Life Cycle Inventories (LCI) have been growing in global databases. Most of the added datasets are for conventional agriculture unit processes and synthetic inputs. The limitation of organic farming LCI data is due to the small scale of certified

1 organic farms representing 0.9% of the world's agriculture land (Willer et al., 2013).
2 However, many non-certified farms apply organic management to recycle nutrients,
3 e.g. N, P and K, from manures, crop residues and cover crops.

4
5 The Swiss centre for life cycle inventories continues the development of, and hosts,
6 the ecoinvent[®] LCI (Frischknecht and Rebitzer 2005) on-line database to allow data
7 exchange and to support comparative LCA on expanded boundaries of different
8 sectors and regions. Based on the ecoinvent implementation, Nemecek and Kägi
9 (2007) developed the LCI of Swiss and European agricultural production systems and
10 expanded it for U.S. systems (Kägi and Nemecek, 2007). The agriculture LCI (ag-
11 LCI) defines the agricultural system boundaries to include the supply chains of
12 synthetic fertilizers and pesticides, unit processes such as land operations, and field
13 emissions. Compatible database technology is implemented in the LCA commons on-
14 line database at www.lcacommons.gov. Unit processes of LCI of field crop
15 production were harmonized from United States Department of Agriculture (USDA)
16 databases and are implemented in the LCA commons (Cooper et al., 2012; 2013).
17 Bellon-Maurel et al. (2014; 2015) demonstrated the concept of traceability data (Tr-
18 data) using the information and communication technologies (ICTs) to collect farm-
19 level data and generate new LCI datasets utilizing global LCI databases (e.g.
20 ecoinvent[®]) and emission models. LCA software tools are needed to automate LCA
21 computations using the large LCI datasets (Schenck, 2013).

22
23 In this paper, a framework of LCA was examined to compare environmental impacts
24 of agricultural systems and benchmark ERC from organic management. The
25 framework used OpenLCA (GreenDelta, Berlin, Germany) to build LCI datasets in
26 the hierarchical order of inputs, land operation unit processes, and cropping system
27 inventories interacting with ag-LCI databases and a cropping system simulation
28 model, CropSyst, developed by Stöckle et al. (2003; 2014). Environmental impacts
29 and potential ERC of organic farming were demonstrated by (1) comparisons of
30 carbon footprints of inputs and land operations and by (2) comparing environmental
31 impacts of organically managed potato production from one case study farm in
32 southwest Washington State, USA versus other inventoried potato production
33 systems. Due to the geographical limits of the case study data, comparison results
34 cannot be generalized between potato production systems. The goal from the

comparisons in this paper was not to perform a standard comparative LCA but it was mainly to examine the framework highlighting main organic management differences and effects on the impacts that would guide future case studies.

2. Methods

2.1. Interactive framework

An interactive framework (Fig. 1) was implemented to develop a structured database, to enable future comparative LCA of organic farming following ISO standards 14040 and 14044 (ISO, 2006^{a,b}) to evaluate carbon footprints according to ISO 14067 (ISO, 2013) and to expand the analysis to more impact categories such as water related impacts according to ISO14046 (ISO, 2011). The framework comprised inventory and LCIA methods presented by boxes enclosed by solid lines (Fig. 1). It was made interactive by exchanging data with LCI databases and packages developed by others (external packages) as indicated by boxes enclosed by dashed lines. In addition to unifying namespaces of inputs and processes that allow most LCA tools exchange inventory data, the framework unified land operation definitions (section 2.3) to interact with soil and crop simulations (section 2.4) and data entry web interface. Data sets were imported/exported as indicated by the arrows in Fig. 1

Fig. 1 Interactive Life Cycle Assessment (LCA) framework

The implemented inventory database was structured in layers to allow flexible scoping of the assessment. Assessment started from inputs, then to operations, to crops, to land-units and finally to whole farm enterprises. The inventory was implemented in OpenLCA that is open-source under public license allowing multi-user participation in collecting farm-level data for the LCI implementation using a

baseline inventory. Like most of the commercially available LCA software, OpenLCA allows exchange of datasets among most of the LCI global databases. A baseline inventory was adapted from the ecoinvent LCI to use similar evaluation boundaries and to allow comparative analysis with other regional and global case studies.

An inventory of land operations was developed based on the database of the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) (USDA-ARS, 2013). Inputs to each operation were quantities of the unit processes and machinery using the same boundaries implemented in ecoinvent. Crop and soil dynamics were implemented in the external package, CropSyst, also according to RUSLE2 definitions. Thus the feedback of simulated emissions and impacts from CropSyst, RUSLE2, and ecoinvent LCA implementation used consistent operations, definitions/selections, and boundaries.

A list of carbon footprints, expressed as CO₂-equivalents (CO₂-eq), normalized per unit quantity of the baseline inventory was evaluated using the 100-year global warming characterization proposed by IPCC (2007). The normalized list was implemented in the web interface, OFoot (<https://ofoot.wsu.edu/>), allowing the comparison of carbon footprints on the basis of a farm configuration entered by the user. Also, a model was implemented to evaluate the carbon footprint of RUSLE 2 operations so that the user could optimize the carbon footprint while configuring crop management. The crop management activities were simulated by CropSyst (Stöckle et al., 2003; 2014) to evaluate environmental interventions. Crop management and simulation results were used to complete crop and farm LCIs.

2.2. Baseline organic farm inventory

A baseline inventory was built to establish a common and initial inventory to expedite building new agricultural LCI's. The baseline inventory was also shared commonly between organic farming systems to benchmark and compare different management. The baseline inventory was based on the operations of 5 commercial organic farms in Washington State. The equipment, inputs, processes, and yields were assessed by in-depth personal communications, farm records, and on-farm observations. The

analyzed operations were built as unit processes in the OpenLCA hierarchical order. The top levels of the hierarchical assessment were fertilizers, pest management, and general agricultural inputs and machinery. Typical materials used in these subsystems on commercial organic farms are outlined in the next subsections. A LCI of organic potato production was implemented to give examples of organic farming inputs and processes. Also, examples of the imported ecoinvent processes were given in each section.

2.2.1. Fertilizers

Certified organic fertilizers were assumed from biogenic or natural mineral sources. Fertilizer impacts were considered for processing/mining, transportation, land application, and emissions from nutrients. The emissions associated with their application to soil were evaluated according to their degradation rates defined in CropSyst simulations. CropSyst simulated nitrous oxide and ammonia emissions, nitrate and ammonium leaching and carbon sequestration. Relevant treatment and transportation processes were imported from the ecoinvent database. Treatment processes were organized under subcategories of bioprocessing and physical processing. Bioprocessing considered composting, onsite fermentation and anaerobic digestion. The first two were considered for the treatment of biowaste and animal manure and were imported from the ecoinvent ag-LCI. The anaerobic digestion of biowaste process was imported from the ecoinvent bioenergy LCI (Jungbluth et al., 2007).

The physical processing of drying and grinding were considered analogous to the processes used for poultry manure and bone meal, respectively. Both poultry and bone meal process inventories were imported from the ag-LCI. The drying process for other organic fertilizer such as blood meal was altered by eliminating the ammonia emission from the poultry manure drying process. Inventory of processing of natural mineral rock phosphate and limestone were imported from ecoinvent inventories of inorganic phosphorus fertilizer and construction material (Althaus et al., 2007^a; Kellenberger et al., 2007), respectively. In the organic potato case study farm, compost and bone meal fertilizers were applied at 1.1 and 1.0 t/ha, respectively.

2.2.2. Pest Management

Tillage operations are the primary operation for weed management in the Pacific Northwest (PNW) organic farming and are covered in more detail in the land operations section 2.3. Three other categories for pest management were considered: Sheet ground covers, mulch, and organic sprays. A variety of sheeting materials from paper, plastic, and fabric are used as inputs for weed control, pest control, and weather protection in organic production. Production processes of typical mulches and covering material were imported from ecoinvent renewable material, plastics and paper LCIs (Althaus et al., 2007^b; Hirschier, 2007). Production processes of oils, soaps and microorganisms which are often used in organic management were represented by similar ecoinvent unit processes for the production of plant oils, degradable detergents and fermentation products.

The inventory of a typical pest control process was modeled using the exact quantities of these agronomical inputs, and the fuel and machinery used in their application. For example, weeds were controlled in the organic potato production case study using a hand driven rototiller. Example inputs to this pest control process were 6.9 kg/ha of gasoline and the allocated mass of the rototiller per unit area, 0.4 kg/ha. The rototiller was modeled as agricultural machinery as described in the next section.

2.2.3. General agricultural inputs and machinery

Other general input inventories were imported and adapted for the PNW to evaluate the organic farming management using the same ecoinvent-defined boundary of agricultural production. Baseline inventories were added for several energy inputs including: electricity sourced from an average technology mix in the US imported from the ecoinvent database, typical electricity in the PNW assuming 90% hydropower, and off-grid electricity using typical photovoltaic installations. The processes of fuel production were from ecoinvent fuels inventory. Local biodiesel production from processed vegetable oil was added. Inventories of emissions from fuel combustion were added as separate unit processes.

Machinery manufacturing inventories of tractors, tillage, and harvest machinery were imported from the ecoinvent inventory of agricultural means of production.

Machinery inventories were normalized by unit weight so they could be scaled according to typical equipment used in land operations as described in the next section. Transportation baseline inventory was evaluated for typical means of transporting agronomic inputs and other supplies to the farm. Means of local transportation included utility truck, tractor and trailer, van or passenger car. Their inventories and fuel use were presented in mass-distance (t·km) functional units so that they could be scaled according to bookkeeping records of the farms.

Infrastructure inventories were implemented for typical buildings, greenhouse types, fencing and equipment storage sheds. These inventory items were evaluated using ecoinvent values for construction materials and adding other typical materials in the PNW such as softwood. Carbon footprint was the only considered environmental metric for the added material to allow future case studies of carbon footprint of a whole farm enterprise. Other metrics of newly added building materials were considered beyond the scope of this paper.

2.3. Land operation inventory

2.3.1. RUSLE operations

Standard land operation records were imported from the RUSLE2 database to evaluate the LCI of each operation. The records comprised soil physical disturbances and machinery operation parameters. Soil physical disturbances such as changes in void ratio were imported to CropSyst for use in simulating emissions of cropping systems. Descriptions of machinery use, fuel consumption and average tractor speed were the imported parameters for each operation. Using the imported parameters, the inventory of each RUSLE2 operation was evaluated according to Equations 1-5 for a land unit of one hectare. The input LCI_{inv} boundary comprised the baseline inventories of machinery LCI_{ma} , infrastructure LCI_{infr} and fuel LCI_{fuel} :

$$LCI_{inv} = \{LCI_{ma}, LCI_{infr}, LCI_{fuel}\} \quad \text{Eq. 1}$$

The LCI_{ma} was scaled from the input unit processes (P_i) of tractor and machinery production and depreciation of tires according to their weight (W_i) and the ratio of the operation time (T_{op}) to their useful life times (T_i):

$$LCI_{ma}[\text{ha}^{-1}] = T_{op} \left[\frac{\text{hr}}{\text{ha}} \right] \cdot \sum_i \frac{W_i[\text{kg}]}{T_i[\text{hr}]} \cdot P_i[\text{kg}^{-1}] \quad \text{Eq. 2}$$

Where T_{op} was evaluated as function of the implement width (w_{ma}) the average speed (v) as defined by the RUSLE2 imported parameters.

$$T_{op} \left[\frac{hr}{ha} \right] = \frac{10,000 \left[\frac{m^2}{ha} \right]}{v \left[\frac{m}{hr} \right] \cdot w_{ma} [m]} \quad \text{Eq. 3}$$

Similarly, the infrastructure such as workshops and sheds used to maintain and store the equipment were scaled by the allocated areas (A_j) and the T_{op} ratio to the infrastructure lifetime (T_j) as

$$LCI_{infr} [ha^{-1}] = T_{op} \left[\frac{hr}{ha} \right] \cdot \sum_j \frac{A_j [m^2]}{T_j [hr]} \cdot P_j [m^{-2}] \quad \text{Eq. 4}$$

The amounts of consumed fuel (F) were used to scale the inventories of fuel production (P_{pr}) and combustion (P_{em}) unit processes and evaluate the LCI_{fuel}

$$LCI_{fuel} [ha^{-1}] = F \left[\frac{kg}{ha} \right] \cdot \{P_{pr}, P_{em}\} [kg^{-1}] \quad \text{Eq. 5}$$

2.3.2. Organic farming operations

Estimates of organic farming operation carbon footprints were based on the RUSLE operations that produce equivalent soil physical disturbances, e.g. tillage depth. The estimates considered typical weight, trailing power/methods and dimension that were scaled to smaller equipment than used in RUSLE-defined operations. The farm equipment and implements used for small-scale potato production were Farmall A tractor, John Deere 35 hp tractor, Mantis light tiller, basket weeder, 3-point tandem disk (1.5m width), one-row potato digger, spreader, 1.5m rotary mower, rototiller, 1.2m flail mower and single shank subsoiler. The equipment were arranged for the case study farm operations as shown in Table 1 indicating fuel type and equivalent RUSLE operations. Carbon footprints of the listed organic farm operations were compared with the footprints of equivalent RUSLE operations. The comparisons on the operations level did not consider soil emissions. Soil emissions were added when considering crop, rotation and whole farm management levels.

Table 1 Case study farm operations

2.4. Cropping system emissions and comparison

Environmental emissions were estimated per unit area from CropSyst simulations of carbon and nitrogen cycles considering typical crop rotations, climate and soil profile of a case study farm in southwest Washington State, USA. Organic potato production was simulated as part of a 10 year rotation. Three consecutive rotations were simulated considering 30 years of climate variation. Typical precipitation during winter seasons is 700-1000mm with relatively dry summers. A winter cover crop was rotated each year with summer cash crops to minimize erosion and runoff. Drip tape irrigation was applied for summer crops e.g. organic potato, to supplement water supply. Water emissions were considered only to the ground water compartment due to the minimized runoff.

The organic potato was rotated with 8 other annual crops and one full year cover crop. Winter cover crops and the full year cover crop of rye-vetch were disked in as organic sources of nitrogen. The rotation is alternated spatially on the farm on 10 equivalent plots. The 30-year simulation was repeated 10 times, incrementing the rotation by 1 crop each time so that all crops were simulated in each of the 30 years of weather data. From the simulated nitrogen cycle, emissions of nitrous oxide and leaching of nitrate and ammonium were integrated over periods of organic potato seasons and averaged over the repeated production years of the repeated rotations and simulations. Emissions of cover crop seasons were evaluated similarly.

The impacts were evaluated for two time-windows. One time-window was considered for the potato production season only which extended from the time the crop was planted until it was harvested. The other time window considered the yearly rotation with the cover crop. Results from both of the time-windows were compared with other cropping systems whose inventories were imported from the ecoinvent ag-LCI. Impacts were compared with ecoinvent inventoried potato production systems to demonstrate the application of the framework in LCIA of different systems. The ecoinvent inventoried systems were for average USA conventional potato production from irrigated lands and both integrated and organic production of potato from rain fed lands in Switzerland (Swiss). We assume the comparison is adequate for the framework demonstration since the organic potato case study LCI was built using the baseline inventory imported from ecoinvent and using the same system boundaries of

ecoinvent agriculture inventories. However, the comparisons should not be considered conclusive as a standard competitive LCA of potato production systems due to differences in climates, power sourcing and methods of evaluating emissions of reactive nitrogen compounds. Effects of such differences were evaluated in the contribution analysis to impacts. Contribution analysis was performed to evaluate ERC related to organic management and to differentiate them from those related to the external factors.

Phosphorous cycle was not simulated for the case study. The leaching levels of phosphorous were therefore estimated by using the same procedure implemented for the ecoinvent ag-LCI (Nemecek and Kägi, 2007) and by adjusting the regression factors for no manure application and high biomass recycling.

2.5. LCIA methods

OpenLCA implementations of LCIA methods were used to be consistent with ecoinvent definitions (Frischknecht et al., 2007). Climate change impacts were evaluated using the 100 annum (100a) characterization factors (IPCC 2007). Global Warming Potential (GWP) was quantified in the reference unit, kg CO₂-eq. The GWP 100a was evaluated for all inputs and was normalized by their reference units. The GWP was also evaluated to compare RUSLE operations and the size-adjusted operations of the case study organic farm.

Other impact categories were evaluated according to the methods in the US EPA-developed Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) (Bare, 2002). In addition to GWP, TRACI methods were used to quantify the global ozone depletion impact using the reference unit of kg chlorofluorocarbon equivalent (kg CFC-eq). TRACI was also used to quantify acidification in moles SO₂-eq, eutrophication in kg N-eq, photochemical oxidation in kg O₃-eq, and resource depletion using fossil fuels in MJ surplus. Version 2.1 of TRACI was used since it implements USEtox® (www.usetox.org) and toxicities were evaluated in comparative toxic units (CTUh,e) for both human (h) and ecosystems (e) impacts. TRACI methodologies were developed specifically for the United States using input parameters consistent with USA locations. The US average inventory of

conventional potato production systems was used to benchmark organic potato production cases. Impacts were normalized by the USA 2008 average emissions per capita according to Ryberg et al. (2014) to determine the most critical impact in the different potato production systems. Accordingly, the normalized results were presented in person-equivalents (P-Eq) to quantify ERC in analogy to the common use of the P-Eq unit describing the size/demand of environmental services, e.g. for wastewater treatment. Additionally, the framework was flexibly implemented to evaluate impacts using both per unit-area and per crop-mass functional units. Land operations were inventoried per unit area and yields were inventoried for crops to allow the use of both functional units.

3. Results

3.1. Embedded carbon of inputs

GWP-100a results were normalized to reference units of each input in the baseline inventory (supplementary data S1). For fertilizers, anaerobically bioprocessed fertilizer contributed lower GWP per unit of wet weight than either thermally or physically (e.g. ground) processed fertilizers. Anaerobically digested fertilizer with 85-90 % moisture content had $2.6\text{E-}6 \text{ kg CO}_2\text{-eq kg}^{-1}$ compared to thermally processed fertilizer (e.g. feather meal) having $5.02\text{E-}1 \text{ kg CO}_2\text{-eq kg}^{-1}$. However, the latter is much drier. Drying the digested material in on-site fermentation piles with agricultural residues reduced moisture but raised the footprint to $1.24\text{E-}2 \text{ kg CO}_2\text{-eq kg}^{-1}$. Aerobically composted and bagged fertilizer footprint was the same order of magnitude as grinded and mined fertilizers. Aerobically composted commercial fertilizer had $3.6\text{E-}1 \text{ kg CO}_2\text{-eq kg}^{-1}$ compared to ground bone meal of $2.9\text{E-}1 \text{ kg CO}_2\text{-eq kg}^{-1}$ and mined rock phosphate of $2.1\text{E-}1 \text{ kg CO}_2\text{-eq kg}^{-1}$.

For pest management, embedded carbon footprint ($\text{kg CO}_2\text{-eq ha}^{-1}$) of material inputs for covering, mulching and/or spraying operations are orders of magnitude higher compared to mechanical operations. For example, the production of typical paper sheets for mulching to control weeds had $8.6\text{E-}1 \text{ kg CO}_2\text{-eq kg}^{-1}$. One kg of mulching paper was used in one of the focus farms to cover 8 m^2 and was used for one growing season. This resulted in $1.1\text{E+}3 \text{ kg CO}_2\text{-eq ha}^{-1}$ compared to the alternative rototiller operation of $2.8\text{E+}1 \text{ kg CO}_2\text{-eq ha}^{-1}$ for each tillage pass. The carbon footprint for the

operation of spraying is low compared to the production of typical organic sprays. Operating a typical tractor and trailed sprayer resulted in $1.1\text{E}+1 \text{ kg CO}_2\text{-eq ha}^{-1}$. The carbon footprint for the production of typical organic sprays ranged from 1 to $2.5 \text{ kg CO}_2\text{-eq kg}^{-1}$.

Since typical PNW electrical power is 90% hydro the electrical energy footprint is $7.4\text{E}-2 \text{ kg CO}_2\text{-eq kWh}^{-1}$ compared to the US average of $7.6\text{E}-1 \text{ kg CO}_2\text{-eq kWh}^{-1}$. Solar power using typical photovoltaic 3 kWp slanted roof installation further reduced the electrical power production footprint on the case study farm to $6.7\text{E}-2 \text{ kg CO}_2\text{-eq kWh}^{-1}$. Similarly, the use of locally produced biodiesel reduced the carbon footprint by $3.2 \text{ kg CO}_2\text{-eq kg-diesel}^{-1}$ compared to combustion of conventional diesel. This significant reduction in carbon footprint took into account the slight increase of the biodiesel production footprint, i.e. $0.68 \text{ kg CO}_2\text{-eq kg}^{-1}$ from esterification of used vegetable oil compared to $0.6 \text{ kg CO}_2\text{-eq kg}^{-1}$ of conventional diesel.

3.2. Carbon footprints of land operations

In Fig. 2, carbon footprints of operations on the studied organic farm (horizontal axis) were compared with equivalent RUSLE operations (vertical axis). The regression line with a slope of $1.07 > 1.0$ (the slope of the equivalence line) indicated a similar carbon footprint on a ha^{-1} basis of comparable RUSLE operations when using smaller equipment typical on our test-case organic farm. However, the small value of $R^2=0.29$ indicated the high scatter of footprints. Small equipment operations above the equivalence line in Fig. 2 were 0.4 to 0.8 the carbon footprint of the equivalent RUSLE operations using heavier equipment. Small operations managing crop residues through mowing and disking were under the equivalence line with 1.4 to 1.8 times larger footprint.

Fig. 2 Comparison of carbon footprints of small farming equipment used on the studied farm vs. the equivalent operations using large equipment of large-scale intensive agriculture.

3.3. Impacts of cropping systems

Defining the organic potato management as flows of the baseline inventory resulted in the LCI dataset of the organic potato production case study (supplementary data S2). LCIA-TRACI method was applied to the LCI dataset and other ecoinvent inventoried potato production systems. Normalized impact results per kg dry weight of potato in Fig. 3 were used to compare TRACI impact categories among conventional (US), integrated (Swiss), and organic (Swiss) production/cropping systems to the small organic farm (US) impacts within the potato growing season or the entire potato and cover crop year. It should be noted that this scaling considered equal significance of the different impact categories in each system, i.e. no weighing factors were applied to reflect the importance of certain categories. The differences among impacts were in orders of magnitude as shown by the log-scaled vertical-axis of person-equivalents (P-Eq). As shown by sorting the impact categories in a descending order of P-Eq of

1 the case study organic system (organic US), eutrophication was the highest impact
2 ($3.06\text{E-}05$ P-Eq) for that cropping system. The total normalized impact for the organic
3 US system during the crop season was $1.1\text{E-}4$ P-Eq. Eutrophication was 27% of this
4 total when considering the potato season only while it was 79% when considering the
5 full year including rainy season and cover crop. Due to the increase in eutrophication
6 the total normalized impact of the yearly potato production including cover crop was
7 $5.1\text{E-}4$ P-Eq, i.e. 5 times of the total impact during the potato production season
8 alone. However, the total normalized impact of the case study organic cropping
9 system was less by orders of magnitude when compared with other cropping systems
10 with totals of $5.3\text{E-}03$, $3.5\text{E-}3$ and $1.7\text{E-}3$ for conventional US, integrated Swiss and
11 organic Swiss, respectively. Manure application in the organic Swiss case increased
12 eutrophication and ecotoxicity impacts compared to the organic US case
13 incorporating cover crop and compost. As shown in Fig. 3, the major mitigations to
14 global impacts by the case study of organic potato production system were in the
15 ecotoxicity and human toxicity impact categories with 2-3 orders of magnitude
16 reductions in P-Eq when compared to conventional US production. The significant
17 reductions of impacts by implementing organic management were also confirmed by
18 the per unit area impacts (Table 2).

Fig. 3 Comparisons of normalized ecological impacts of producing 1 kg (dry weight) potato from organic, conventional, and integrated agricultural systems.

Impacts of potato production in organic, conventional, and integrated systems per hectare are listed in Table 2. On an area basis, the ecological impact benefits of the US organic system were even greater than on a dry weight basis because on an area basis yield differences were not considered. Dry mass yield and moisture content are also listed so per unit mass assessments can be calculated. Organic potato yields were about 65% of conventional yields. The results indicated that the 10 TRACI impacts were generally reduced by implementing integrated and organic management with the largest reductions achieved under organic management of potato production in the case study farm. Toxicity impacts (no. 2, 5 & 6) were reduced by more than 99% by the case study organic management. Corresponding toxicity reductions of integrated management were 38%, 64% and 61%. The other Swiss organic management reduced eco-toxicity impact by 97% while reductions of human toxicity impacts were similar to integrated management.

Eutrophication in the organic case study was 97% less than in conventional production. When the entire calendar year was considered, the organic case study eutrophication impact was 40% that of conventional. The reduction was still substantial compared to the other integrated Swiss and organic Swiss systems of 12% and 22 % compared to conventional, respectively. The same trend of impact reductions was observed in acidification. Compared with conventional US, other impacts were reduced by 65%-90% in the US organic case study during the production season, or 50%-85% when including the full calendar year and cover crop impacts.

Table 2 Per hectare impacts of potato production under different cropping management systems

Contribution analysis indicated that the use of metam-sodium and chlorothalonil pesticides in conventional US potato cropping system contributed 39% and 37% of the ecotoxicity impacts, respectively. Metam-sodium was not used in integrated management while neither was used in organic management.

In the conventional US cropping of potatoes, the irrigation system contributed 52% of the human health – carcinogenic impacts of which one third was from sourcing energy from the average US grid and the rest was mainly from irrigation system building material and agricultural machinery. Chromium VI associated with chromium steel in heavy equipment was the main contributing material flow to the estimated carcinogenic impacts. Human health non-carcinogenic impacts in the conventional system were 24% from the irrigation system, 16% from the inorganic fertilizer production, 15% from pesticides and the remainder was mainly from land operations.

4. Discussion

The implemented framework of this study supports the evaluation of agricultural impacts during selecting inputs, equipment and planning land operations, crops and

1 rotations. Exchanging data with external databases and packages supports
2 comparative studies to evaluate ERC's as follows:

4 4.1. Agricultural input selection

5 The GWP of the available options for many types of inputs differs by orders of
6 magnitude which lead to large differences among farming systems with respect to the
7 total carbon footprint. The carbon footprint can be evaluated interactively while
8 building a farm inventory allowing selection among alternative equipment, fertilizers,
9 pest management procedures and energy sources. The framework handles scaling
10 interactively with the web interface external package OFoot leading to two
11 advantages. The first advantage is the on-line support to farmers' decision-making in
12 reducing the carbon footprints of their farms. A similar tool "Cool Farm Tool"
13 (Hillier et al., 2011) was successfully implemented in spreadsheet to scale GWP of
14 inputs and estimate the farm carbon footprint using farm available data. The second
15 advantage of the implemented framework is the ability to retrieve farm data to build
16 crop and farm inventories in standard database format. The databases can then be
17 further analyzed to evaluate other impacts such as those defined by the EPA TRACI
18 methods (Bare, 2002). Also, collected inventories are compatible to contribute to LCI
19 databases such as the online crop LCI on the USDA digital commons (Cooper et al.,
20 2012)

22 4.2. Land operation scaling

23 The analyzed inventory of RUSLE operations allows comparisons of the small farm
24 operations to better evaluate emissions. The carbon footprint results of the small farm
25 operations indicated 50-80% differences compared to equivalent operations using
26 larger size implements and tractor ratings. There is a general tendency of reducing
27 total impacts using smaller equipment. However, the results show a tradeoff between
28 emission reduction using lighter equipment and the emission increase with additional
29 power needed to manage crop residues and cover crops. Incorporation of crop
30 residues requires more power and consumes more fuel that requires proper selection
31 of equipment as demonstrated by the wide range of rototilling operations. Although
32 mowing for coarse chopping or shredding can be accomplished efficiently using small
33 equipment, flail mowing such as prior to crop residue incorporation has a greater

energy demand. RUSLE2 does not differentiate between these types of mowing operations, but this is possible using an equipment-specific inventory. More passes are required to finish the same area consuming more fuel and increasing the carbon footprint despite the reduced traction of the smaller disking implements. The same trade off was observed between reduction of total emission with relative increase of onsite emissions in Australian organic farming compared to conventional (Wood et al., 2006). The framework would therefore guide growers in selecting the right type of equipment for their land operations. The framework evaluates possible reductions of emissions that could support investment decisions / subsidy structure for agricultural equipment investments.

4.3. Emission reduction credits (ERC)

The LCA framework was used to compare impact categories among different systems with the advantage of the normalization to P-Eq units. It should be noted that this scaling assumes equal significance among impact categories in each system. Also, comparisons of different crop management systems were possible by using the same baseline inventory of supply chains modeled in ecoinvent. The comparison indicated critical categories for further improvement and could be used to estimate ERC of changing crop management.

Eutrophication was the most critical impact in the comparative LCA case study of organic potato production both in the Swiss study and in the present case study. Nitrate and ammonium leaching were the main contributors, especially during the rainy season of the cover crop. While cover crop reduces erosion, its reduction of leaching N was minimal. Higher nitrate leaching is generally observed in cover crop rotations with reduced leaching levels if the cover crop was replaced by vetch and harvested as forage (Gabriel et al., 2013). Also covering and controlled drainage would be an option to reduce leaching for further improvement of the environmental service of the system and for minimizing the losses of the readily available nitrogen needed for high crop yields (Gan et al., 2013). The framework application to estimate and compare LCA impacts, therefore, highlights possible improvements of ERC and triggers new research areas to evaluate agronomic sustainability.

Ecotoxicity impacts are significantly reduced by eliminating pesticide use in organic production. The difference is 3 orders of magnitude when compared to ecotoxicity

impacts of the conventional systems and nearly 2 orders of magnitude compared to the integrated (Swiss) system. The LCA framework could be used to quantify ERCs supporting their trading as offsets to other sectors. Also, through contribution analysis ERCs could be credited to energy, machinery or agronomical sources. The estimated reduction in carcinogenic toxicity of the case study organic potato system could be credited to its use of hydroelectric power for irrigation which would be the same regardless of whether the system was organic or conventional. Also, small farms could be credited to its use of simpler irrigation systems and smaller equipment reducing the use of chromium steel and the associated carcinogenic impacts. On the other hand, the estimated reduction of non-carcinogenic toxicity due to replacing inorganic fertilizer is credited entirely to organic production methods.

5. Conclusions

The examined LCA framework evaluated environmental impacts and emission reduction credits (ERC) from organically managed farming systems. An interactive framework is required to support extension and research activities for further improvement of the ERC while building the organic farming LCI stepwise as follows:

- Base-line inventories of organic farming inputs are imported from global LCI databases to establish a common boundary for the evaluation and comparisons with conventional and other farming systems.
- Unit process inventories of land operations are modeled using inputs from the baseline inventory and using quantities of fuel and machinery use estimated from universal erosion model definitions of agricultural operations.
- Crop inventories are modeled integrating input inventories and land operations unit processes with elementary flows and emissions imported from cropping systems simulation.
- Crop rotation inventories per unit area are built integrating the above components according to defined management and farm spatial configuration that can be traced from case study and information technologies such as the frame work web interface.
- Yields per unit area can be used for allocation and presenting inventories per mass units of products as often traced in agricultural databases.

Accordingly, LCIA methods are calculated on each inventory level. The evaluation of GWP on the first two levels supports extension activities and decisions of selecting inputs and equipment to minimize the carbon footprint. The evaluation of global

1 impacts on the crop and crop rotation levels supports research activities to evaluate
2 ERC from organic farming using other systems as a benchmark. Normalization of
3 impacts using per capita national averages of impacts unifies the scale of different
4 impact categories enabling the comparisons of different systems in units of person
5 equivalents as commonly used for sizing treatment systems. However, this
6 normalization does not consider the significance of particular impact categories and
7 weighing factors need to be applied for more detailed assessment of each system.

9 Therefore, it is recommended to use the implemented framework for further case
10 studies to support mitigation of ecological impacts while supporting adaptation of
11 organic farming ecosystems and enriching their inventories in global LCI databases.

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26

1 **Table 1 Case study farm operations**

Farm operation	Tractor	Implement	Fuel type	RUSLE equivalent
Basket weeding	Farmall A	basket weeder	gasoline	Ridge till
Broadcast fertilizer	John Deere	spreader	diesel	Manure slurry spreader
Disking 1	John Deere	3-point tandem disk	diesel	Disk, tandem secondary
Disking 2	John Deere	3-point tandem disk	diesel	Disk, tandem finishing
Disking and plow	John Deere	3-point tandem disk	diesel	Plow, disk
Harvest	John Deere	one row potato digger	diesel	Harvest, dig root crops
Mow to flail	John Deere	1.2 m flail mower	diesel	Rotary mower or flail shredder
Mow to shred	Farmall A	1.5m rotary mower	gasoline	Rotary mower or flail shredder
Mow to windrow	Farmall A	1.5m rotary mower	gasoline	Mower, windrower
Rip to subsoil	John Deere	Single shank subsoiler	diesel	Subsoiler or Vee ripper
Rototill field	John Deere	rototiller	diesel	Rototiller, field
Rototill rows	Mantis light tiller		gasoline	Rototiller, row cultivator

2

Table 2 Per hectare impacts of potato production under different cropping management systems

No.	Impact categories and yield	Functional unit	Convetional (US)	Integrated Management (Swiss)	Organic (Swiss)	Organic (US) + cover crop impact	Organic (US)
1	Acidification	kg SO ₂ eq ha ⁻¹	59	54	45	9	7
2	Ecotoxicity	CTUe ha ⁻¹	362,274	223,927	11,407	154	141
3	Eutrophication	kg N eq ha ⁻¹	125	111	98	50	4
4	Global Warming	kg CO ₂ eq ha ⁻¹	6,411	3,945	2,913	2,569	1,378
5	Human Health - carcinogenics	CTUh ha ⁻¹	3.59E-04	1.28E-04	1.13E-04	5.12E-06	4.53E-06
6	Human Health - non- carcinogenics	CTUh ha ⁻¹	1.24E-03	4.87E-04	4.88E-04	5.92E-06	5.35E-06
7	Ozone Depletion	kg CFC-11 eq ha ⁻¹	1.32E-03	3.40E-04	1.97E-04	1.55E-04	1.25E-04
8	Photochemical ozone formation	kg O ₃ eq ha ⁻¹	420	314	254	206	145
9	Resource depletion - fossil fuels	MJ surplus ha ⁻¹	6,855	2,875	1,953	1,677	1,390
10	Respiratory effects	kg PM2.5 eq ha ⁻¹	4	3	2	1	1
	Dry weight yield	kg/ha	9020	8309	5269	5830	5830
	Moisture	%	78	78	78	77	77