Int J Life Cycle Assess (2013) 18:331–339
DOI 10.1007/s11367-012-0493-9

Practical recommendations for supporting agricultural decisions through life cycle assessment based on two alternative views of crop production: the example of organic conversion

Kiyotada Hayashi

Received: 30 March 2012 / Accepted: 24 August 2012 / Published online: 8 September 2012

Abstract
Purpose Earlier studies on agricultural life cycle assessment recommend that practitioners use two functional units—product weight and land area—because agriculture entails commodity production and land use. However, there are still ambiguities in this approach from the perspective of decision support. The purpose of this paper is to provide recommendations to support farming conversion decisions on the basis of a framework constructed on two alternative views of agricultural production. Organic conversion of arable farming is selected as a case study.
Methods Four types of conversion were constructed on the basis of land-oriented expression, in which inputs into and outputs from land were depicted, and product-oriented expression, in which inputs into and outputs from products were depicted. Then, the frequencies for each type were counted using LCI databases and data from journal papers.
Results The results can be summarized as follows: (1) trade-off conversion, in which improvements in environmental impacts per area unit are involved in decrease of yield per area unit, is common. (2) Conversion tended to be efficient; that is, environmental impacts per product unit tended to improve. (3) Within trade-off conversion, the conversion tended to be efficient. (4) When conversion was efficient, there were trade-offs.
Conclusions Since the results for one expression were not always derivable from the results for another expression, the recommendation of this study is to use the two expressions complementarily, knowing that win–win conversion is rare. In addition, there is a general recommendation to use decision criteria rather than trying to make decisions on the basis of multiple functional units because comparisons based on the two functional units are not on the same level.

Keywords Arable farming · Decision criteria · Functional unit · Organic conversion · Trade-off · Win–win

Responsible editor: Ivan Muñoz

K. Hayashi (✉)
National Agriculture and Food Research Organization,
Agricultural Research Center,
3-1-1 Kannondai,
Tsukuba, Ibaraki 305-8666, Japan
e-mail: hayashi@affrc.go.jp

1 Introduction

The number of applications of life cycle assessment (LCA) to agriculture has increased recently in pursuit of comprehensive and comparative assessment of agricultural production systems and identification of environmental hot spots and the improvement potential of agricultural practices. One of the distinctive characteristics of the applications is the complementary use of multiple functional units. For example, in earlier review papers, several authors recommend that practitioners use two functional units: product weight and land area (van der Werf and Petit 2002; Halberg et al. 2005; Payraudeau and van der Werf 2005; Hayashi et al. 2007; van der Werf et al. 2007). Indeed, many authors assess environmental impacts both per product unit (for example, per kilogram) and per area unit (for example, per hectare) (Nienhuis and de Vreede 1996; Hanegraaf et al. 1998; Haas et al. 2001; Basset-Mens and van der Werf 2005; Charles et al. 2006; Mouron et al. 2006a; Mouron et al. 2006b; Hayashi 2006; Nemecek et al. 2008; Bartl et al. 2011; Nemecek et al. 2011a; Nemecek et al. 2011b).

However, in order for policymakers and farm managers to use LCA in agricultural decision making such as the selection of alternative agricultural production systems, further scrutiny is necessary, for the following two reasons. First, both indicators, environmental impacts per product unit and those per area unit, are asymmetric. While environmental impacts per product unit consist of outputs (environmental impacts) as numerators and outputs (products) as denominators, environmental impacts per land unit consist of outputs (environmental impacts) as numerators and an input (land) as a denominator. Second, inconsistent recommendations may be derived from two different indicators. Since environmental impacts per product unit are quotients of environmental impacts per land unit divided by product weight per land unit, comparisons based on environmental impacts per product unit are different from comparisons based on environmental impacts per land unit; that is, information about production (product weight per land unit) is not used in the latter.

Recent research trends necessitate dealing with the problem mentioned above. First, increased attention to design problems (the use of mathematical programming to design optimum farm and regional planning from environmental and economic perspectives) necessitates the explicit distinction between product-related and land-related indicators. In other words, since farm planning models can be formulated using multi-objective mathematical programming, and the models maximize farm profit per land unit and minimize environmental impacts per land unit subject to constraints such as the limits of land and labor availability, the solutions are dependent on how to convert original problems into solvable problems (Hayashi 2000). Second, increased attention to coupling multiple criteria decision analysis (MCDA) and LCA (Linkov and Seager 2011) necessitates establishing a relationship between decision criteria in MCDA and impact categories in LCA. Third, an increased interest in biodiversity and ecosystem services may also necessitate the distinction between product-related indicators and land-related indicators because they are closely related to land use. Brandão et al. (2011) used the unit of 1 ha of land for 1 year in assessing soil quality as an indicator for ecosystem services, stressing the importance of the unit of 1 GJ of energy.

The purpose of this paper is to provide recommendations to support farming conversion decisions, a term which is defined here as problems selecting among alternative farming systems, on the basis of a framework constructed on two alternative views of agricultural production: land- and product-oriented expressions. Organic conversion of arable farming is selected as a typical case for the study because of the importance of the transition to sustainable agricultural systems and the availability of data.

2 Methods

2.1 Two alternative views of agricultural production

There are basically two alternative views of agricultural production. One is land-oriented expression and the other is product-oriented expression, as shown in Fig. 1. Since land is a unit (denominator) to measure inputs and outputs in agronomy (Maeder et al. 2002; Cassman et al. 2003), land-oriented expression has been commonly used in LCA of agriculture. In land-oriented expression, the inputs to land are materials such as fertilizers and pesticides and the outputs include products and environmental impacts (hereafter simply “impacts”). For simplicity, inputs such as machinery and infrastructure (capital goods) and outputs such as by-products and waste are not shown in Fig. 1. Product-oriented expression is common in product LCA. In it, inputs to products include materials and land, and outputs are impacts.

In Fig. 1, land and products in the squares are equivalent to functional units. Land-oriented expression corresponds to assessment using a functional unit of land area such as 1 ha. Although we use land area as a function unit in this paper, land area times years (hectare × year) should be the functional unit in the assessment of crop rotation. The land-oriented expression in Fig. 1 illustrates that information on products has also to be considered separately in the assessment. In other words, both yield and impacts have to be used as decision criteria. Product-oriented expression corresponds to assessment using a functional unit of product mass such as 1 kg. The use of other units such as energy content (e.g., megajoules) and monetary values (e.g., yen) can be classified as variations of product-oriented expression.

2.2 Four types of organic conversion

Organic conversion is discussed in this paper as an example of conversion from a farming system to another farming system that is often considered more favorable. Thus, the following explanation should be applicable to other forms of conversion, for example, from conventional production to improved production in which new cultivation technologies are introduced.

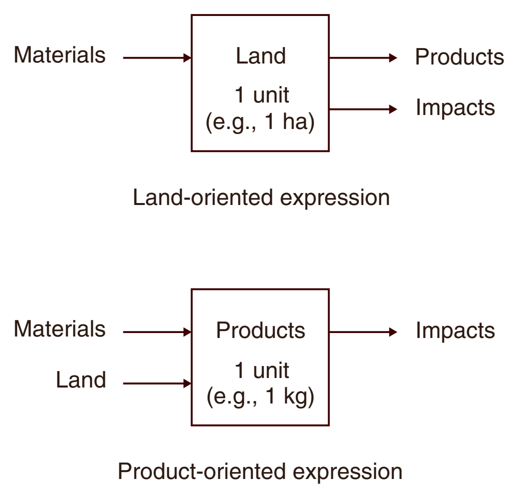

Fig. 1 Two alternative views of agricultural production

The results of the assessment of conversion processes from conventional production (including integrated production) to organic production can be classified into four types using the results obtained from two expressions, as illustrated in Fig. 2. First, there are two types of conversion in the results of assessment based on land-oriented expression: trade-off conversion and non-trade-off conversion. Trade-off conversion is defined as conversion in which improvement in one criterion is accompanied by deterioration of another criterion; it includes win–lose and lose–win conversion. In non-trade-off conversion, simultaneous improvements (win–win conversion) or simultaneous deteriorations of both criteria (lose–lose conversion) are possible.

Second, since we have only one criterion for assessment based on a model of product-oriented expression, this implies simply a win or lose conversion. We say that the conversion is efficient if the impact per product unit is improved through the conversion. We use the term efficient because the impact per product unit is defined as the ratio of the impact per area unit to the yield per area unit.

By combining the two expressions, four types of conversion are defined, as shown in Fig. 2. In order of desirability, we have *A* (win–win and efficient conversion), *B* (trade-off and efficient conversion), *C* (trade-off and inefficient conversion), and *D* (lose–lose and inefficient conversion). Since if the conversion is win–win, it is efficient and if it is lose–lose, it is inefficient; *A* is simply termed win–win conversion and *D* lose–lose conversion.

2.3 Data for counting the frequencies

The data used to count the frequency of the appearance of each type are the results of life cycle impact assessment (LCIA). Two approaches are applied to prepare the data. One is a calculation using published inventory databases and the other uses the results of LCIA from published journal papers.

2.3.1 Calculation using published inventory database

In order to prepare the data (results of LCIA), ecoinvent version 2.2 (Nemecek and Kægi 2007) and ESU life cycle inventory database on demand (hereafter, ESU LCI database) (Jungbluth et al. 2011) were used. The reasons for the use of these databases are as follows: (1) use of a published database is preferable for the purposes of providing traceable system definitions and attaining reproducible results; and (2) use of an LCI database with uncertainty parameters is necessary in order to judge the differences between the impacts before and after the conversion, as illustrated in the next section.

Conversion analyzed in this paper is the transformation from integrated production as conventional production to organic production. The conversion is defined as the change from a steady state of integrated production to a steady state of organic production; thus, it is not the actual conversion process at the farm nor the field experiments on conversion (Hokazono and Hayashi 2012). As shown in Tables 1 and 2, ten crop production processes were selected using ecoinvent 2.2 and 13 vegetable production processes from the ESU LCI database.

The system boundaries for these databases are cradle to gate. The LCIA recommended by the Institute of Environmental Sciences (CML), Leiden University (Guinée 2002), which is implemented in the software SimaPro 7.3 (CML 2 baseline 2000), was used.

2.3.2 Data from journal papers

Another possibility for counting the frequency of appearance for each type is the use of the results of LCA in scientific journal papers if the results contain both impacts per area unit and impacts per product unit. Even if both types of impact were not available, the results could be used to count the frequency if crop yield was indicated. The data available from Nemecek et al. (2011a), in which the results of the DOC (bio-Dynamic, bio-Organic, and Conventional) experiment (Maeder et al. 2002) and the Burgrain experiment (Zihlmann et al. 2004) were reported, were used in this paper. Since these results include information about both impacts per area unit and impacts per product unit and have had analysis of variance (ANOVA) conducted, they were used as a complement to the two databases mentioned already. Lists of farming systems used to assess the conversion are shown in Tables 3 and 4.

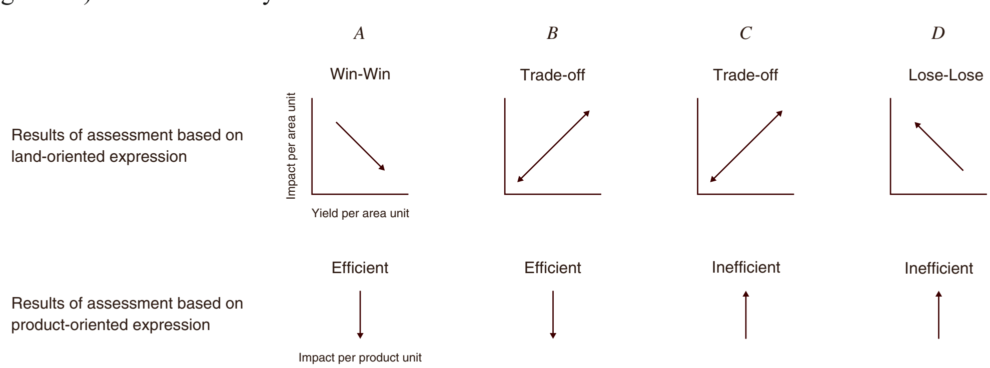

Fig. 2 *A–D* Four combination types of land- and product-oriented expressions

Table 1 List of processes used to assess the conversion: ecoinvent 2.2

Crop name	Process name in ecoinvent 2.2	
	From	To
Barley grains	Barley grains IP, at farm/CH U	Barley grains organic, at farm/CH U
Grain maize	Grain maize IP, at farm/CH U	Grain maize organic, at farm/CH U
Hay intensive	Hay intensive IP, at farm/CH U	Hay intensive organic, at farm/CH U
Potatoes	Potatoes IP, at farm/CH U	Potatoes organic, at farm/CH U
Protein peas	Protein peas, IP, at farm/CH U	Protein peas, organic, at farm/CH U
Rape seed	Rape seed IP, at farm/CH U	Rape seed, organic, at farm/CH U
Rye grains	Rye grains IP, at farm/CH U	Rye grains organic, at farm/CH U
Silage maize	Silage maize IP, at farm/CH U	Silage maize organic, at farm/CH U
Soy beans	Soy beans IP, at farm/CH U	Soy beans organic, at farm/CH U
Wheat grains	Wheat grains IP, at farm/CH U	Wheat grains organic, at farm/CH U

IP integrated production, *CH* Switzerland, *U* unit process

Although Nemecek et al. (2008) provided the results of comparative LCA on two crop rotation systems, the results were not used in this paper because the comparison is not related to organic conversion. Williams et al. (2010) presented comparisons between organic and nonorganic crops (bread wheat and potatoes). However, statistical tests or uncertainty analyses were not given, and thus, the results were not used in this paper.

2.4 Judgment of the difference

There are four approaches to making judgments of the differences between the environmental impacts of conventional (integrated) production and those of organic production. The first is simple judgment, in which numerical values are compared simply with each other. This approach cannot ascertain whether the difference is large enough to be significant. The second approach is the use of empirical rules. Nemecek et al. (2008), for example, compared two crop rotations and classified the impacts of the second crop rotation relative to the first crop rotation into very favorable, favorable, similar, unfavorable, and very unfavorable. Although this approach is useful in indicating the degree of difference empirically, it is difficult to explain the reason why the approach is fair. The third approach is statistical tests. For example, Nemecek et al. (2011a) used an ANOVA. The fourth approach is the use of Monte Carlo methods, in which computational simulation is carried out on the basis of repeated random sampling.

In this study, Monte Carlo analysis was used for data from ecoinvent 2.2 and the ESU LCI database. The uncertainty analysis for comparisons implemented in SimaPro 7.3 was applied in this study; the number of iterations was 1,000 (the default value in SimaPro). We define the environmental impact of a production system P as greater than that of Q if $\Pr(e(P)>e(Q))\geq 0.9$, where $e(\,)$ is the environmental impact of the production system. Because uncertainty data on crop yields were

Table 2 List of processes used to assess the conversion: ESU LCI database

Crop name	Process name in ESU LCI database	
	From	To
Beans	Beans, IP, at farm/CH U	Beans, organic, at farm/CH U
Beet root	Beet root, IP, at farm/CH U	Beet root, organic, at farm/CH U
Broccoli	Broccoli, IP, at farm/CH U	Broccoli, organic, at farm/CH U
Cabbage	Cabbage, IP, at farm/CH U	Cabbage, organic, at farm/CH U
Cauliflower	Cauliflower, IP, at farm/CH U	Cauliflower, organic, at farm/CH U
Chicory	Chicory, IP, at farm/CH U	Chicory, organic, at farm/CH U
Fennel	Fennel, IP, at farm/CH U	Fennel, organic, at farm/CH U
Leek	Leek, IP, at farm/CH U	Leek, organic, at farm/CH U
Onions	Onions, IP, at farm/CH U	Onions, organic, at farm/CH U
Peas	Peas, IP, at farm/CH U	Peas, organic, at farm/CH U
Red cabbage	Red cabbage, IP, at farm/CH U	Red cabbage, organic, at farm/CH U
Savoy	Savoy, IP, at farm/CH U	Savoy, organic, at farm/CH U
Tomatoes	Tomatoes, IP, at farm/CH U	Tomatoes, organic, at farm/CH U

IP integrated production, *CH* Switzerland, *U* unit process

Table 3 List of farming systems used to assess the conversion: the DOC experiment

Combination of farming system and fertilization level	
From	To
C1 (conventional/integrated, half fertilization level)	O1 (bio-organic, half fertilization level)
C1 (conventional/integrated, half fertilization level)	D1 (bio-dynamic, half fertilization level)
C2 (conventional/integrated, normal fertilization level)	O2 (bio-organic, normal fertilization level)
C2 (conventional/integrated, normal fertilization level)	D2 (bio-dynamic, normal fertilization level)

Source: Nemecek et al. (2011a)

not available from ecoinvent 2.2 or the ESU LCI database, uncertainty in environmental impacts per product unit was analyzed using SimaPro 7.3. We call this judgment of differences Monte Carlo judgment. Since the results of statistical tests were available for the DOC and Burgrain experiments, these results were utilized for the judgment of differences. This will be referred to as statistical judgment.

In addition, in order to check the reliability of simple comparisons, which are sometimes the only comparisons possible in real-world applications of LCA, we define reliability of simple comparisons as the ratio of Monte Carlo judgment and statistical judgment to simple judgment (judgment based on simple comparisons).

3 Results

3.1 Trade-off conversion is common

The first result is derived from the land-oriented expression and says that trade-off conversion is common. More precisely, the sum of the number of cases belong to *B* and to *C* is greater than that of *A* and *D*. The result is simply written as $\#B+\#C>\#A+\#D$, where # means the number of elements in the type. We get the following results: 57+6>0+20 for ecoinvent 2.2 (Table 5), 59+22>0+19 for the ESU LCI data base (Table 6), 17+2>0+0 for the DOC experiment (Table 7), and 10+0>0+0 for the Burgrain experiment (Table 8). In other words, 76, 81, 100, and 100 % were the respective trade-off conversions. Concerning differences among impact categories, there are several exceptions. For the ecoinvent 2.2, acidification, eutrophication, and terrestrial ecotoxicity gave a different result: $\#B+\#C<\#A+\#D$. For the ESU LCI database, photochemical oxidation gave the result $\#B+\#C=\#A+\#D$.

3.2 Conversion tends to be efficient

The second result is based on the product-oriented expression and says that conversion tends to be efficient. That is, $\#A+\#B>\#C+\#D$: 0+57>6+20 for ecoinvent 2.2; 0+59>22+19 for the ESU LCI database; 0+17>2+0 for the DOC trial; and 0+10>0+0 for the Burgrain trial. The respective efficient conversions were 69, 59, 89, and 100 %. The percentages were lower than or equal to the percentages for the trade-off conversion. For the ecoinvent 2.2 data, there were the same exceptions in the same impact categories as in the above section. For the ESU LCI database, the results for abiotic depletion, acidification, global warming, and photochemical oxidation were exceptional. For the DOC experiment, there were three exceptions—ozone formation potential, eutrophication potential, and acidification potential—and for the Burgrain experiment, there was one exception—acidification potential.

3.3 Trade-off conversion tends to be efficient

With regard to the third result, we pay attention to the trade-off conversion. This conversion tends to be efficient: $\#B>\#C$, 57>6 for ecoinvent 2.2; 59>22 for the ESU LCI database; 17>2 for the DOC experiment; and 10>0 for the Burgrain experiment. The percentages of efficient conversion to trade-off

Table 4 List of farming systems used to assess the conversion: the Burgrain experiment

	Farming system	
	From	To
Cash crop rotation[a]	Intensive integrated production	Organic production
Feed crop rotation[b]	Intensive integrated production	Organic production

Source: Nemecek et al. (2011a)

[a] 2-year rotation: potato–(green manure)–winter wheat–(grass clover ley)–grain maize–spring barley–grass clover ley, (catch crops are written in parentheses)

[b] 3-year rotation: silage maize–spring oats–winter barley–grass clover ley

Table 5 The number of cases for each type: ecoinvent 2.2

Impact category	A^{a}	B^{a}	C^{a}	D^{a}	Sum[a]
Abiotic depletion	0/0	8/8	1/2	0/0	9/10
Acidification	0/0	1/1	1/2	7/7	9/10
Eutrophication	0/0	2/3	1/3	4/4	7/10
Global warming (GWP100)	0/0	4/6	1/4	0/0	5/10
Ozone layer depletion (ODP)	0/0	9/10	0/0	0/0	9/10
Human toxicity	0/0	8/8	2/2	0/0	10/10
Fresh water aquatic ecotoxicity	0/0	8/9	0/0	1/1	9/10
Marine aquatic ecotoxicity	0/0	7/9	0/0	1/1	8/10
Terrestrial ecotoxicity	0/0	2/2	0/1	7/7	9/10
Photochemical oxidation	0/0	8/9	0/1	0/0	8/10
Sum	0/0	57/65	6/15	20/20	83/100

[a]Monte Carlo judgment/simple judgment

conversion were 90, 73, 89, and 100 %, respectively. Acidification in ecoinvent 2.2; abiotic depletion and photochemical oxidation in the ESU LCI database; ozone formation potential, eutrophication potential, and acidification potential in the DOC experiment; and acidification potential in the Burgrain experiment were exceptional impact categories.

3.4 There are trade-offs in efficient conversion

In the fourth result, we restrict our attention to efficient conversion. When conversion is efficient, there are trade-offs: $\#A<\#B$ and $\#A=0$. In other words, there was no win–win conversion. Results showed 0<57 for the ecoinvent 2.2; 0<59 for the ESU LCI database; 0<17 for the DOC experiment; and 0<10 for the Burgrain experiment. Concerning the results for each impact category, there were no exceptions for ecoinvent 2.2 and the ESU LCI database. Although there were some exceptions for the DOC and Burgrain experiments, their relationship is $\#A=\#B$ and not $\#A>\#B$.

3.5 Reliability of simple comparisons

The last result is supplementary to the above results. That is, the topic is the reliability of simple comparisons. Since Monte Carlo simulations and statistical tests are not always applicable to comparative LCA, it is useful to get results about the reliability of simple comparisons. First, the results classified as win–win and lose–lose conversion are more reliable than those considered trade-off conversion. If we use mathematical notation, the results can be written as follows: $\#B/\#B^{S}<\#D/\#D^{S}=1$ and $\#C/\#C^{S}<\#D/\#D^{S}=1$, where the superscript S means that the judgments are based on simple comparisons. Since $\#A=0$ for ecoinvent 2.2 and the ESU LCI database and $\#A=\#D=0$ for the DOC and the Burgrain experiment, we concentrate on types B, C, and D for ecoinvent 2.2 and the ESU LCI database. Second, the results classified as B are more stable than those classified as C; that is, $\#B/\#B^{S}>\#C/\#C^{S}$. This relation is applicable to all the data used in this paper. These results illustrate that we have to be cautious about simple comparisons if there are trade-offs in the land-oriented expressions, especially if the type is recognized as C.

Table 6 The number of cases for each type: ESU LCI database

Impact category	A^{a}	B^{a}	C^{a}	D^{a}	Sum[a]
Abiotic depletion	0/0	4/4	4/7	2/2	10/13
Acidification	0/0	6/6	4/4	3/3	13/13
Eutrophication	0/0	7/10	2/2	1/1	10/13
Global warming (GWP100)	0/0	4/7	2/2	4/4	10/13
Ozone layer depletion (ODP)	0/0	6/11	2/2	0/0	8/13
Human toxicity	0/0	5/5	2/7	1/1	8/13
Fresh water aquatic ecotoxicity	0/0	8/9	1/2	2/2	11/13
Marine aquatic ecotoxicity	0/0	5/7	2/4	2/2	9/13
Terrestrial ecotoxicity	0/0	13/13	0/0	0/0	13/13
Photochemical oxidation	0/0	1/2	3/7	4/4	8/13
Sum	0/0	59/74	22/37	19/19	100/130

[a]Monte Carlo judgment/simple judgment

Table 7 The number of cases for each type: the DOC experiment

Impact category[a]	*A*[b]	*B*[b]	*C*[b]	*D*[b]	Sum[b]
Energy demand	0/0	2/4	0/0	0/0	2/4
Global warming potential	0/0	3/4	0/0	0/0	3/4
Ozone formation potential	0/0	0/0	1/4	0/0	1/4
Eutrophication potential	0/0	0/2	1/2	0/0	1/4
Acidification potential	0/0	0/4	0/0	0/0	0/4
Aquatic ecotoxicity potential	0/0	4/4	0/0	0/0	4/4
Terrestrial ecotoxicity potential	0/0	4/4	0/0	0/0	4/4
Human toxicity potential	0/0	4/4	0/0	0/0	4/4
Sum	0/0	17/26	2/6	0/0	19/32

[a] Original expressions were used, although they are different from Tables 5 and 6. P- and K-resource demand and land occupation were not included

[b] Statistical judgment/simple judgment

4 Discussion

4.1 Derivation from one expression to another

This section clarifies situations where only the results of assessment based on the land-oriented expression or the product-oriented expression are available. First, we will consider the situation in which only impacts per area unit are available. In this situation, if organic conversion is win–win, the conversion is efficient, and if it is lose–lose, the conversion is inefficient. However, if the conversion entails trade-offs, the conversion can be efficient or inefficient. This implies that both conventional and organic productions are non-dominated. Thus, integration rules have to be introduced in order to judge which is preferable for decision makers, although the ratio is not the only criterion for making a final decision.

Second, in the situation where only impacts per product unit are available, if the conversion is efficient, then it is win–win or entails trade-offs. That is, the results of assessment based on the product-oriented expression cannot distinguish win–win conversion from trade-off conversion, although they illustrated that there were no win–win conversion. In other words, although theoretically the efficiency (the ratio of impact per area unit to yield per area unit) cannot identify the difference between win–win conversion and trade-off conversion, there is empirically no win–win conversion. Even if there is win–win conversion, it must be rare. Thus, our next topic of discussion is why trade-offs are pervasive.

Table 8 The number of cases for each type: the Burgrain experiment

Impact category[a]	*A*[b]	*B*[b]	*C*[b]	*D*[b]	Sum[b]
Energy demand	0/0	2/2	0/0	0/0	2/2
Global warming potential	0/0	2/2	0/0	0/0	2/2
Ozone formation potential	0/0	1/2	0/0	0/0	1/2
Eutrophication potential	0/0	1/2	0/0	0/0	1/2
Acidification potential	0/0	0/1	0/1	0/0	0/2
Aquatic ecotoxicity potential	0/0	1/2	0/0	0/0	1/2
Terrestrial ecotoxicity potential	0/0	1/2	0/0	0/0	1/2
Human toxicity potential	0/0	2/2	0/0	0/0	2/2
Sum	0/0	10/15	0/1	0/0	10/16

[a] Original expressions were used, although they are different from Tables 5 and 6

[b] Statistical judgment/simple judgment

4.2 Why are trade-offs pervasive?

One of the main reasons why trade-offs are pervasive in the results is that the conversion analyzed in this paper is the transformation from integrated production to organic production. Both production systems can be matured at least in developed countries, in which certification systems and product labeling are established. They can be depicted as a change from (b) to (a) on a production-possibility frontier, as shown in Fig. 3. In contrast, win–win conversions such as a change from (c) to (a) may be possible for agricultural systems that have the potential to be improved. A similar discussion is available in the biodiversity literature as follows.

Clough et al. (2011) analyzed the relationship between biodiversity and crop productivity and presented a contrast between the following agricultural systems: (1) temperate grasslands and arable fields, as well as large-scale tropical plantations, which entail trade-offs between conservation and agricultural production, and (2) tropical countryside, which allows for joint improvement of biodiversity and yield because intensity of agricultural inputs and efficiency of management are often low. We are now able to give an interpretation of this distinction as follows: (1) trade-off conversion corresponds to the transformation among the

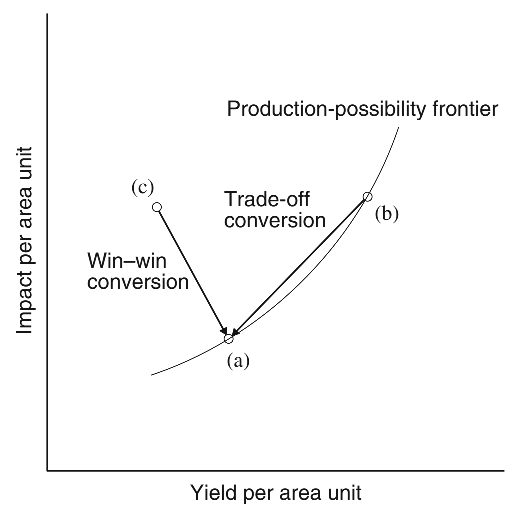

Fig. 3 Schematic diagram to illustrate why trade-off conversion is common for matured agricultural systems

former agricultural systems; and (2) win–win conversion can be realized in the latter agricultural systems.

Although we restrict our attention to product weight for a product-oriented expression, if we measure product by monetary units garnered (if we use the functional unit of income), win–win conversions are highly attainable under the condition that price premiums and government support are available. The reason that product weight was used in this paper is that even if the conversion is win–win when monetary units are used, crop yields are still important, because food consumption is a primary human need. In this case, we have to be explicit about general trends in the yield difference between organic and conventional agriculture (de Ponti et al. 2012; Seufert et al. 2012).

5 Conclusions

Two recommendations are provided as final conclusions of this study.

5.1 Use decision criteria rather than functional units

The first recommendation is that decision criteria be used rather than trying to make decisions on the basis of multiple functional units. If the recommendation was the use of multiple functional units, the comparison between impacts per area unit and impacts per product unit would seem to be helpful. However, as already discussed, this comparison based on the functional units is not fair because the product information (yield) is not contained in impacts per area unit. In contrast, if the recommendation is the use of decision criteria, the problem should be recognized as a two-criteria decision problem. The two criteria are impacts per area unit (to minimize) and yield per area unit (to maximize). The ratio of the former to the latter becomes impacts per product unit, which can be recognized as an integrated upper-level criterion. The weighted addition of impacts per area unit and yield per area unit is another integrated upper-level criterion.

5.2 Use both expressions complementarily, knowing that win–win conversion is rare

The second recommendation concerns the difference between the land-oriented and product-oriented expressions. Efficient conversion in the product-oriented expression can be both win–win and trade-off conversion in the land-oriented expression, as explained in Section 4 above. This implies that if we only rely on the product-oriented expression, we cannot detect whether the efficient organic conversion is win–win. In other words, product LCA of organic conversion cannot reveal whether research and development of organic agricultural technologies are win–win in terms of the land-oriented expression. In the empirical results based on the available LCI databases, it was illustrated that the conversion tends to entail trade-offs. This means the development of win–win organic agricultural technologies is challenging, at least in developed countries. Therefore, detecting whether win–win conversion is realized is very important.

On the other hand, trade-off conversion can be both efficient and inefficient. Without defining a procedure to integrate the two criteria, it is impossible to judge which agricultural system is preferable. As already stated, there are two methods to do this: one is the use of the ratio and the other is the use of weighted addition. If there are trade-offs in the conversion and no reasons to justify the use of the ratio for integrating the two criteria, the distinction between types *B* and *C* becomes meaningless.

Therefore, the second recommendation should be to use both expressions complementarily, while understanding the following two facts: first, although type *B* is dominant, it is based on the assumption that the use of the ratio is justified for the integration of the two lower-level criteria; second, trade-offs in the land-oriented expression have to be analyzed, as does product LCA based on the product-oriented expression. The two upper-level criteria should be used complementarily.

Acknowledgments This work was supported in part by the Japan Society for the Promotion of Science Grant-in-Aid for Scientific Research [(C) 20580256 and (C) 23580321].

References

Bartl K, Gómez CA, Nemecek T (2011) Life cycle assessment of milk produced in two smallholder dairy systems in the highlands and the coast of Peru. J Clean Prod 19(13):1494–1505

Basset-Mens C, van der Werf HMG (2005) Scenario-based environmental assessment of farming systems: the case of pig production in France. Agr Ecosyst Environ 105(1–2):127–144

Brandão M, Milà i Canals L, Clift R (2011) Soil organic carbon changes in the cultivation of energy crops: implications for GHG balances and soil quality for use in LCA. Biomass Bioenerg 35(6):2323–2336

Cassman KG, Dobermann A, Walters DT, Yang H (2003) Meeting cereal demand while protecting natural resources and improving environmental quality. Annu Rev Env Resour 28:315–358

Charles R, Jolliet O, Gaillard G, Pellet D (2006) Environmental analysis of intensity level in wheat crop production using life cycle assessment. Agr Ecosyst Environ 113(1–4):216–225

Clough Y, Barkmann J, Juhrbandt J, Kessler M, Wanger TC, Anshary A, Buchori D, Cicuzza D, Darras K, Putra DD, Erasmi S, Pitopang R, Schmidt C, Schulze CH, Seidel D, Steffan-Dewenter I, Stenchly K, Vidal S, Weist M, Wielgoss AC, Tscharntke T (2011) Combining high biodiversity with high yields in tropical agroforests. P Natl A Sci 108(20):8311–8316

de Ponti T, Rijk B, van Ittersum MK (2012) The crop yield gap between organic and conventional agriculture. Agric Syst 108:1–9

Guinée JB (ed) (2002) Handbook on life cycle assessment, operational guide to the ISO standards. Kluwer Academic Publishers, Dordrecht

Haas G, Wetterich F, Köpke U (2001) Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. Agr Ecosyst Environ 83(1–2):43–53

Halberg N, van der Werf HMG, Basset-Mens C, Dalgaard R, de Boer IJM (2005) Environmental assessment tools for the evaluation and improvement of European livestock production systems. Livest Prod Sci 96(1):33–50

Hanegraaf MC, Biewinga EE, Van der Bijl G (1998) Assessing the ecological and economic sustainability of energy crops. Biomass Bioenerg 15(4–5):345–355

Hayashi K (2000) Multicriteria analysis for agricultural resource management: a critical survey and future perspectives. Eur J Oper Res 122(2):486–500

Hayashi K (2006) Environmental indicators for agricultural management: integration and decision making. Int J Mater Struct Reliab 4 (2):115–127

Hayashi K, Gaillard G, Nemecek T (2007) Life cycle assessment of agricultural production systems; current issues and future perspectives. In: Good Agricultural Practice (GAP) in Asia and Oceania. Food and Fertilizer Technology Center for the Asian and Pacific region, Taipei, pp 98–110

Hokazono S, Hayashi K (2012) Variability in environmental impacts during conversion from conventional to organic farming: a comparison among three rice production systems in Japan. J Clean Prod 28:101–112

Jungbluth N, Flury K, Büsser S, Stucki M, Frischknecht R (2011) Life cycle inventory database on demand: EcoSpold LCI database of ESU-services. Uster, Switzerland

Linkov I, Seager TP (2011) Coupling multi-criteria decision analysis, life-cycle assessment, and risk assessment for emerging threats. Environ Sci Technol 45(12):5068–5074

Maeder P, Fliessbach A, Dubois D, Gunst L, Fried P, Niggli U (2002) Soil fertility and biodiversity in organic farming. Science 296 (5573):1694–1697

Mouron P, Nemecek T, Scholz RW, Weber O (2006a) Management influence on environmental impacts in an apple production system on Swiss fruit farms: combining life cycle assessment with statistical risk assessment. Agr Ecosyst Environ 114(2–4):311–322

Mouron P, Scholz RW, Nemecek T, Weber O (2006b) Life cycle management on Swiss fruit farms: relating environmental and income indicators for apple-growing. Ecol Econ 58(3):561–578

Nemecek T, Kægi T (2007) Life Cycle Inventories of Agricultural Production Systems, ecoinvent Report No. 15. Agroscope Reckenholz-Tænikon Research Station ART, Swiss Centre for Life Cycle Inventories, Zurich and Dübendorf

Nemecek T, von Richthofen JS, Dubois G, Casta P, Charles R, Pahl H (2008) Environmental impacts of introducing grain legumes into European crop rotations. Eur J Agron 28(3):380–393

Nemecek T, Dubois D, Huguenin-Elie O, Gaillard G (2011a) Life cycle assessment of Swiss farming systems: I. Integrated and organic farming. Agric Syst 104(3):217–232

Nemecek T, Huguenin-Elie O, Dubois D, Gaillard G, Schaller B, Chervet A (2011b) Life cycle assessment of Swiss farming systems: II. Extensive and intensive production. Agric Syst 104 (3):233–245

Nienhuis JK, de Vreede PJA (1996) Utility of the environmental life cycle assessment methods in horticulture. Acta Hortic 429:531–538

Payraudeau S, van der Werf HMG (2005) Environmental impact assessment for a farming region: a review of methods. Agr Ecosyst Environ 107(1):1–19

Seufert V, Ramankutty N, Foley JA (2012) Comparing the yields of organic and conventional agriculture. Nature 485(7397):229–232

van der Werf HMG, Petit J (2002) Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods. Agric Ecosyst Environ 93(1–3):131–145

van der Werf HMG, Tzilivakis J, Lewis K, Basset-Mens C (2007) Environmental impacts of farm scenarios according to five assessment methods. Agr Ecosyst Environ 118(1–4):327–338

Williams AG, Audsley E, Sandars DL (2010) Environmental burdens of producing bread wheat, oilseed rape and potatoes in England and Wales using simulation and system modelling. Int J Life Cycle Assess 15(8):855–868

Zihlmann U, Dubois D, Tschachtli R (2004) Integrierter und biologischer Anbau im Vergleich–Anbausystemversuch Burgrain. Resultate aus 12 Jahren Forschung (1991–2002). Schriftenreihe der FAL, vol 52. Agroscope FAL Reckenholz, Zürich