A multi-attribute decision method for assessing the overall sustainability of crop protection strategies: a case study based on apple production in Europe

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Abstract: Although several alternative pest management strategies are available, crop protection in general and apple crop protection in particular often relies on pesticides. This is largely because multiple environmental and economic aspects or attributes must be simultaneously considered by crop managers, which makes it difficult for them to determine whether one strategy is more sustainable than another. In our study, we investigated the elements that must be considered to obtain a clear and useful assessment of sustainability. We present a system-description tool created especially for life cycle assessment (assessment of energy use and ecotoxicity), environmental risk assessment, and full-cost calculations. Using the various results from these assessments as qualitative attributes, we designed a multi-attribute tool that allows us to integrate sustainability attributes over five levels into an overall sustainability rating. To demonstrate the transparency of this method and how it enables decision makers to deal with complexity, we use the method to assess different crop protection systems used in apple production. Although, the multi-attribute decision method provided a reasonable overall assessment of the sustainability of different protection systems, the assessment could be substantially influenced by the selection of rating scales and decision rules. Therefore, the rating scales and decision rules should be carefully defined and discussed among the research teams. In our case, experts have participated from five European countries.

Keywords: multi-attributive decision making, apple orchard, crop protection strategy, sustainable development, life cycle assessment (LCA), SYNOPS, full-cost calculation

Introduction

European agricultural policy requires the implementation of integrated pest management (IPM) by 2014. The goal is to promote crop protection strategies that are less reliant on pesticides (ENDURE 2009). All members of the EU will have to propose a national action plan to implement IPM strategies adapted to regional conditions. Although methods and tools to evaluate the overall sustainability (including environmental and socio-economic aspects) of such region-based IPM strategies are needed, they are largely unavailable. In contrast, assessments of single aspects of sustainable development have often been published. For environmental aspects of the sustainability of agricultural systems, Foster et al. (2006) provide a review for European countries, mainly based on “life cycle assessment” methodology. Methods that include both environmental and socio-economic aspects are provided by the “response induced sustainability evaluation” or RISE (Grenz et al. 2009) and by the concept of “sustainability solution spaces” (Wiek and Binder 2005; Castoldi et al. 2007). These tools, however, do not attempt to aggregate the various aspects of sustainability into a single rating of the overall sustainability of a system.

Multi-attributive decision making offers a methodological framework for defining hierarchical trees of attributes that generate an overall sustainability rating (Bockstaller et al. 2008; Sadok et al. 2009). This has been demonstrated by Bohanec et al. (2008), who applied a multi-attribute model for economic and ecological assessment of genetically modified crops, and by Lô-Pelzer et al. (2009), who evaluated innovative crop-protection strategies for arable production systems. These multi-attributive studies share an important characteristic, which is that they facilitate consideration of system complexity. The number of attributes used in these models is very high, i.e., the models often include more than 80 attributes on more than seven hierarchical levels.

Although such large “attribute trees” can easily be handled by computer programs (Bohanec 2009), much effort is required to understand and communicate the cause-and-effect relations contained in such models. Transparency should be enhanced so that the logic in the model can be understood, evaluated, and modified as needed.

The goal of this paper is to investigate the methodological elements that need to be considered to obtain transparency in sustainability assessment. An example concerning crop protection systems in apple production is used to demonstrate the transparency of this method. The rating scales and decision rules used in the sustainability assessment described here were defined by a group of experts who had participated in the EU-FP6 project ENDURE.

Scheme for sustainability evaluation

We propose a scheme for sustainability assessment of orchard and other cropping systems that includes five elements. The assessment begins by describing the farming-system parameters (Fig. 1a). The settings of these parameters are then used to conduct quantitative assessments referring to the main dimensions of sustainability, which are in our case ecology and economics (Fig. 1b). The diverse output variables of the assessments or “basic attributes” are then entered at the bottom of a hierarchical attribute tree (Fig. 1c). Here, the quantitative results are transformed into qualitative ratings in order to aggregate them into attributes of higher levels (Fig. 1d). For optimising crop protection systems, however, we need to know which parameters substantially influence the assessment of overall sustainability (Fig. 1e). Such cause-and-effect relations can be obtained by investigating the results from top to bottom in the scheme described in Figure 1. In the following sections, we describe the components of Figure 1 in greater detail.

Insert Fig. 1 about here

System-description tool

Our study compares crop protection strategies that reduce pesticide application with a baseline system (BS) that strictly relies on pesticide application. We distinguished therefore an advanced system (AS) that replaces pesticides as much as possible by alternative methods that are available on the market and an innovative system (IS) that replaces pesticides by alternative methods that are currently used in field trials or laboratories but are not available on the market. The system descriptions include detailed information concerning the active ingredients applied, the dosages applied, and the time of application (the calendar week). Such parameters must be related to expected yield levels. Expected yields can be estimated with the “target yield approach” (Bera et al. 2006). The target yield approach takes into consideration the efficiency of crop protection parameters for achieving the desired target parameter level (e.g., yield) for a particular orchard system with given context parameters. Figure 2 illustrates how the definitions of crop protection parameters are embedded within context parameters and target parameters in our “system-description tool”. By keeping context parameters and target parameters for a region constant, we were able to compare the sustainability of different crop protection strategies (i.e., BS vs. AS and IS) while assessing the whole farming system.

Insert Fig. 2 about here

Quantitative assessment methods

Life cycle assessment (LCA)

The LCA considers not only impacts related to the use of pesticides but also environmental impacts related to pesticide production and transport. The LCA also includes other activities and their related inputs (resource use) in an apple orchard over a season, i.e., fertiliser, machinery, buildings, hail net, and field operations such as harvesting and mulching. LCA does not include the creation and uprooting of the orchard, irrigation, and post-harvest processes like storage.

The design of the LCA follows the principles outlined by ISO (2006). Values from system-description parameters (Fig. 2) for apple orchards are transformed into the life cycle inventory, which is used to evaluate the environmental effects. We used the life cycle inventories from the ECOINVENT database version 2.01 (Frischknecht et al. 2007; Nemecek and Kägi 2007) to assess the infrastructure, inputs, and processes used in the apple orchards. The models used to estimate the various direct field emissions (i.e., NH_3, N_2O, P_2O_5, NO_3^-, heavy metals, and pesticides) are described in the SALCA method (Gaillard and Nemecek 2009; Nemecek et al. 2005, 2008).

The following sustainability attributes were derived as part of the LCA in this study: terrestrial and aquatic ecotoxicity potential of toxic pollutants were calculated according to Guinée et al. (2001); human toxicity potential of toxic pollutants via exposure through food, tap water, and air were calculated according to Guinée et al. (2001); demand for non-renewable energy resources was estimated according to Hischier et al. (2009); global warming potential over 100 years was considered as described in IPCC (2006); and eutrophication potential (the impact of the losses of N and P to aquatic and terrestrial ecosystems) was calculated according to the EDIP97 method (Hauschild and Wenzel 1998).

SYNOPS

The indicator model SYNOPS assesses the risk caused by pesticide drift. In particular, the model assesses the risk for organisms living in terrestrial (i.e., soil and field-margins) and aquatic (i.e., surface water) habitats. It combines pesticide-use data, including different degrees of drift-reduction measures, with environmental conditions (e.g., distance from the orchard to surface water). Chemical, physical, and eco-toxicological properties of applied active ingredients are taken into account (Gutsche and Strassemeyer 2007). In general, the acute and chronic risk potentials are calculated as exposure-toxicity ratios (ETR) for reference organisms such as earthworms for soil, bees for the aboveground area in the crop and in the crop borders, and daphnia, algae, and fish for surface water. Time-dependent pesticide concentration curves are used to derive the acute and chronic risk potentials by relating pesticide concentration in the environment to the lethal concentration (LC50) and the no-effect concentration (NOEC). For each crop protection system under study, the indicator model SYNOPS was applied to assess the region-specific environmental risk potentials. The region-specific and field-related environmental conditions like slope, soil type, and climate were derived from a spatial database, which was developed within the EU-Project HAIR (2007).

The following sustainability attributes were derived from the SYNOPS assessment in this study: terrestrial acute risk; terrestrial chronic risk; aquatic acute risk; and aquatic chronic risk.

Full-cost calculation

Orchards are capital- and labour-intensive perennial systems. Income may vary considerably among years depending mainly on variation in fruit yield and the proportion of 1st-class fruit (Mouron et al. 2007). In addition to calculate average annual income, our economic assessment therefore determines variability in income based on the standard deviation of yield and the proportion of 1st-class fruit as defined in system-description parameters. Dramatic yield loss related to the proportion of years with less than half of the average harvest is also taken into account.

Full-cost principles designed especially for perennial tree crops are applied as described by Mouron et al. (2006b). These full-cost principles evaluate the grower's capacity to amortise or reinvest, and they therefore refer to long-term viability. In particular, cost of production includes all inputs as well as labour costs (those of the grower and of the hired workforce) and depreciation for investments (mainly the cost for establishing the orchard). Total revenue considers only the amount of apples sold and price; the same prices per kilogramme and per fruit class are used for all orchard systems within a region (i.e., premium prices are not considered). Direct payments (i.e., money from the government to promote IPM) are not included in the revenue calculation. These limitations for calculating the revenue were necessary because premium prices and direct payments related to IPM have yet to be realised in most countries.

The following sustainability attributes were derived from full-cost assessment in this study: family income per hour; total production cost per kilogramme of 1st-class apples; net profit per hectare; income variability; invested capital per hectare; and return on investment (i.e., net profit per invested capital).

The calculations were conducted with the managerial-economic software tool Arbokost (Arbokost 2009). This full-cost calculation tool is designed especially for perennial crops.

Sustainability-rating tool

Building a hierarchical attribute tree

The attribute tree was built both from the top-down and from the bottom-up (Fig. 3). From the top-down and according to the "areas of protection" described by Udo de Haes and Lindeijer (2002), the direct sub-attributes of *Ecological sustainability* are *Resource use*, *Environmental quality*, and *Human toxicity*. With regard to apple production, environmental attributes were chosen according to Mouron et al. (2006a, 2006b) and Mila i Canals et al. (2007).

According to Lô-Pelzer et al. (2009), the sub-attributes of *Economic sustainability* are *Profitability, Production risk*, and *Financial autonomy*.

From the bottom-up, the basic ecological attributes were derived from the LCA and SYNOPS. Because the rating of ecotoxicity is the main attribute that is optimised in this research, the ecotoxicity attribute has many sub-attributes. The basic attributes concerning the economic sustainability of orchard systems were selected based on previous studies (Mouron et al. 2007; Bravin et al. 2010).

Insert Fig. 3 about here

Rating basic attributes

The numeric values derived from the assessment methods must be rated as to whether they differ substantially from a baseline system (BS). We used five classes for rating basic and aggregated attributes: much worse than BS, worse than BS, similar to BS, better than BS, and much better than BS.

Basic attributes with strictly positive numeric values require a rating scale that prevents the change of the rating with a shift in the reference system (i.e., a shift in BS). Therefore, the boundary between similar and better is the reciprocal of that between similar and worse, and the boundary between better and much better is the reciprocal of that between worse and much worse. Figure 4 shows the asymmetric rating scales we used for LCA results according to Nemecek et al. (2005). The range for the class “similar” is wider for ecotoxicity and human toxicity attributes than for nutrient and resource management attributes because the methodologies for assessing ecotoxicity are less reliable than those for assessing nutrition and resource management.

For basic attributes that can potentially have negative or positive numeric values (*Family income, Net profit*, and *Return on investment*), we used symmetric rating scales, assuming that a deviation from the reference system (i.e., BS = 100%) in the desired direction is of the same magnitude as a similar deviation in the undesired direction. Here is an example of a symmetric rating scale: similar to BS = 90–110%; better than BS = 110–140%; worse than BS = 60–90%.

Insert Fig. 4 about here

Rating aggregated attributes

In multi-attribute models, decision rules define how the many sub-attributes are aggregated into one assessment of an attribute (Bohanec et al. 2008). Each aggregate attribute in the model (Fig. 3) has an associated set of rules that determine how the aggregation is done. In principle, the rules represent attitudes and preferences of the decision makers; in our case, the rules were specified jointly by experts from five European countries, who were partners in the EU-FP6 project ENDURE.

Tab. 1 shows an example of decision rules that aggregate two sub-attributes into an aggregate attribute. In this case, the two sub-attributes contribute equally to the aggregate attribute; consequently, they are of equal importance and have equal weights. Further it is assumed that if the two sub-attributes do not differ in their classes for a particular rule (for example, if both are rated as “similar” to BS), the aggregated attribute will have the same rating class as its sub-attributes (Tab. 1, No. 1, 7, 13, 19, 25). If the ratings for two sub-attributes differ by two to four classes, the aggregated attribute will be assigned the class between those of the sub-attributes (Tab. 1, No. 3, 5, 9, 11, 12, 15, 17, 21, 23). In all other cases, the assumed rule for aggregation is as shown in Tab. 1 (No. 2, 4, 6, 8, 10, 14, 16, 18, 20, 22, 24).

Insert Tab. 1 about here

Example of an overall sustainability rating

We compared different apple protection systems under European conditions with the goals of reducing ecotoxicity and maximising overall sustainability. Therefore, we defined a baseline system (BS), an advanced system (AS), and an innovative system (IS). The BS operates only with pesticides within the framework of good agricultural practice. The AS aims to replace pesticides as much as possible with available alternative methods, and the IS has the same goal but also uses alternative methods that are currently used in field trials but that will not be on the market for 10–20 years. Both AS and IS represent integrated pest management principles (IPM). The following assumptions for the crop protection parameters were made:

- Arthropod control
  - Alternative methods applied for AS and IS: Mating disruption, attract and kill, microbial control, sanitary methods, mass trapping, exclosure netting, predators and parasitoids
  - Number of insecticide applications: BS = 12, AS = 8, IS = 4
- Disease control:
  - Alternative methods applied for AS and IS: Resistant cultivars, sanitation, antagonistic microorganisms
  - Number of fungicide applications: BS = 7, AS = 4, IS = 3
- Weed control
  - Alternative methods applied for AS and IS: Cover crop from mid-June to harvest with mowing, mechanical weeding
  - Number of herbicide applications: BS = 3, AS = 2, IS = 2

The sustainability assessment was conducted with the programme DEXi (Bohanec et al. 2009). We used the previously described hierarchical attribute tree (Fig. 3), rating scales (Fig. 4), and decision rules (example in Tab. 1). The resulting ratings for the sustainability attributes are presented in Tab. 2. The ratings indicate that in this example the *Ecological-economic overall sustainability* (attribute No. 1) did not differ substantially between AS, IS, or BS, i.e., both AS and IS were “similar” to BS. This might seem surprising because AS and IS considerably reduced the applications of pesticides compared to BS. We can now investigate the reasons for this outcome.

First, the rating of the attribute *Ecotoxicity* (Tab. 2, No. 9) was improved by AS and IS as expected; the rating was improved by one class with AS and by two classes with IS. This is mainly due to improvements among the sub-attributes of *Ecotoxicity* (i.e., attributes No. 10–23). However, *Environmental quality* (Tab. 2, No. 8), which is one level higher in the attribute tree, did not differ for AS and BS. This lack of difference is explained by the ratings of the three sub-attributes of *Environmental quality*, namely *Impact on beneficial organisms*, *Global warming potential,* and *Global eutrophication* (Tab. 2, No. 24–26). *Environmental quality* contributes together with *Resource use* and *Human toxicity* to the top attribute of the environmental branch of the tree, which is *Ecological sustainability* (Tab. 2, No. 2). On this level, AS remains similar to BS, and IS is rated higher by one class. When the rating for *Ecological sustainability* is considered together with the rating from the top attribute of the economic branch, i.e., *Economic sustainability* (Tab. 2, No. 30), it is clear that the AS got a rating of "similar" for the overall sustainability because both sub-attributes of overall sustainability were rated "similar". In the case of IS, one sub-attribute of overall sustainability was rated with "similar" and the other was rated "better". According to the decision rules of Tab. 1, the aggregated rating will then be "similar". We point out that the decision rules of Tab. 1 were those that we selected for this example. It would also be possible to define the decision rule as "similar & better = better". As a consequence, the rating of the overall sustainability of IS would be rated higher for one class. This demonstrates the importance of the choice of decision rules in generating aggregate ratings.

Insert Tab. 2 about here

Conclusions

Using apple production in Europe as an example, we have shown how complex systems that include many attributes can be assessed for overall ecological and economic sustainability. We emphasise that the result of such a multi-attribute sustainability assessment might be substantially different depending on definitions and settings of several elements. To obtain transparency of the assessment results, we identified the following tasks:

1. A well-structured system-description tool must be developed to define and control the size of the attribute tree. Defining crop protection parameters in relation to fixed context and target parameters helps decision makers interpret the outcome of the assessment.
2. Established assessment methods such as Life Cycle Assessment, SYNOPS, and full-cost calculation should be applied to ensure that the quantitative analysis is state of the art. Use of these methods also ensures that the models underlying these calculations and the associated uncertainties are clearly described.
3. For the translation of quantitative assessment results into qualitative rating classes, asymmetric scales need to be defined if the numeric result cannot be less than zero. Developers and user of this approach to sustainability assessment must recognise that the definition of rating scales might substantially influence the overall sustainability rating.
4. The rating of aggregated attributes depends on decision rules because certain combinations of sub-attribute ratings might be interpreted differently according to subjective preferences. Thus, like the definition of rating scales, the definition of decision rules can substantially influence the overall sustainability rating.

We suggest that these four tasks should be defined by research teams. In this study, the knowledge of experts from five European countries was combined.

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Figures

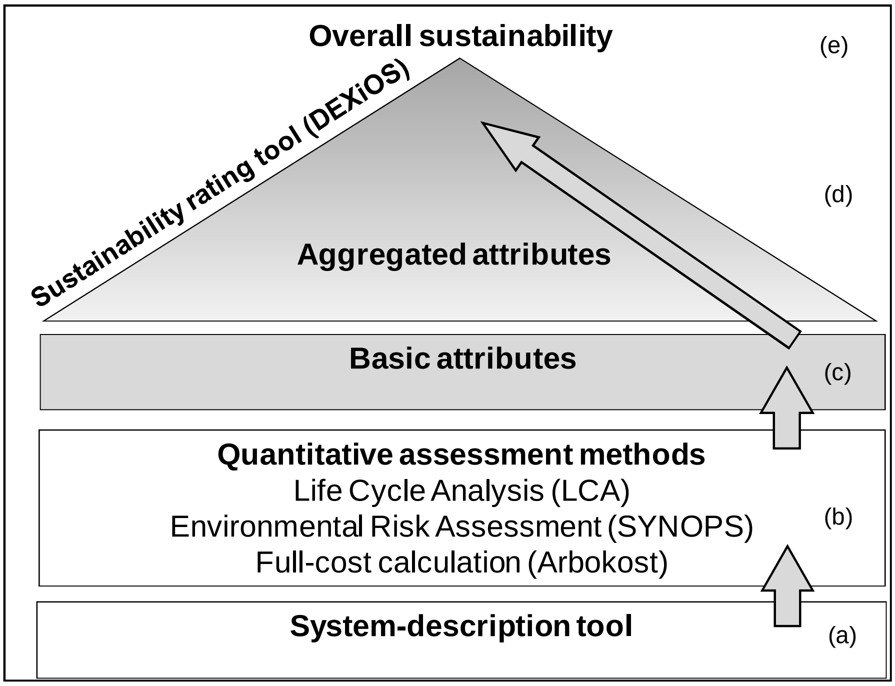

Fig. 1 Scheme for assessing the overall sustainability of crop systems

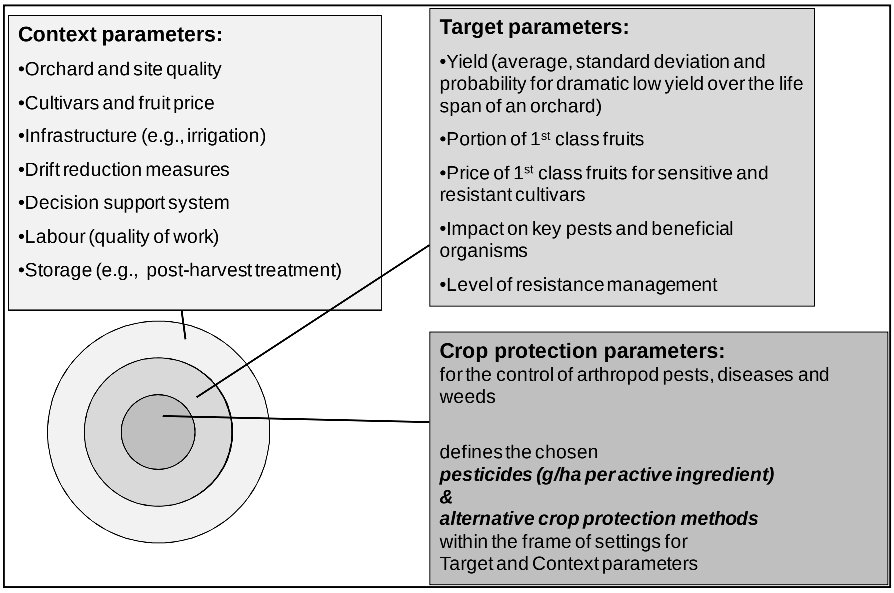

Fig. 2 Three types of system-description parameters for defining crop protection strategies for apple production.

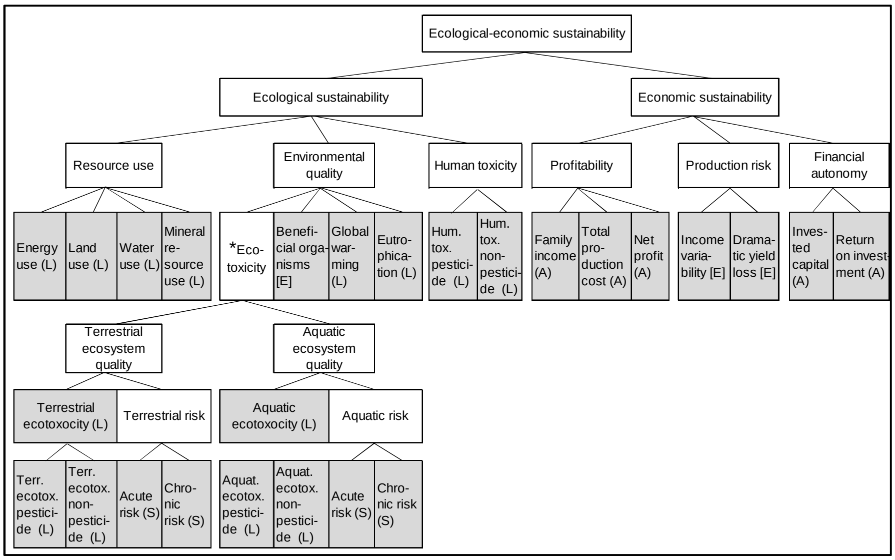

Fig. 3 Hierarchical attribute tree for assessing the ecological and economic sustainability of orchard systems. Basic attributes are in grey boxes. * Ecotoxicity is the main attribute that is optimised in this research. Letters in parentheses refer to the assessment method: L = Life Cycle Assessment, S = SYNOPS, A = Arbokost, E = Expert estimation.

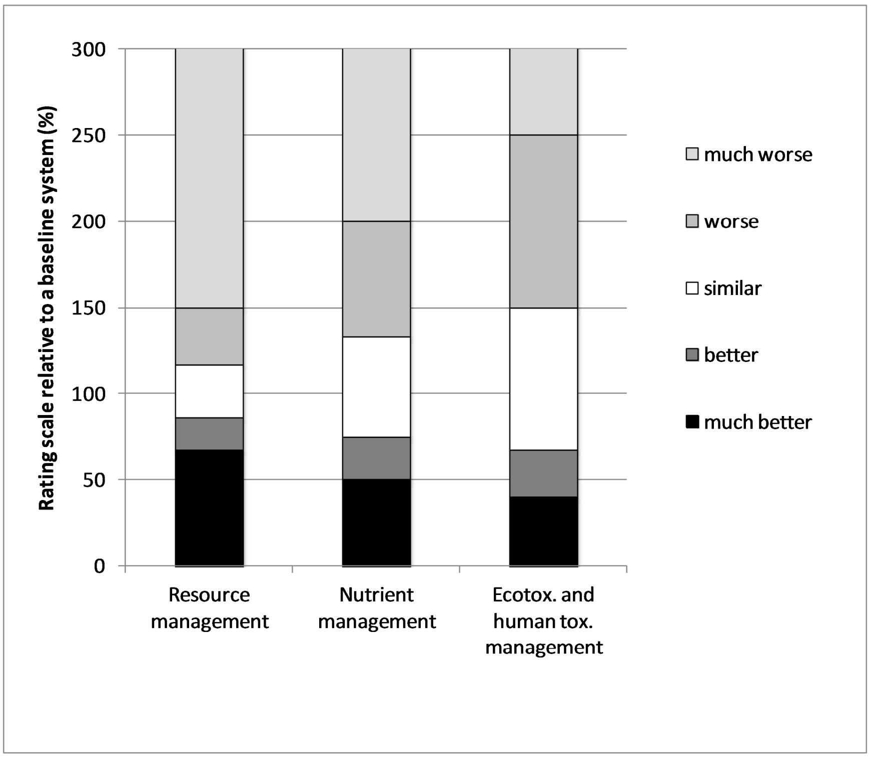

Fig. 4 Asymmetric scales for rating Life Cycle Assessment results in relation to a baseline system (= 100%)

Tables

Table 1 Decision rules for rating aggregated attributes with equal weights

Decision rule number	**Sub-attribute 1** e.g., Aquatic ecotoxicity related to pesticide inputs	**Sub-attribute 2** e.g., Aquatic ecotoxicity related to non-pesticides inputs	**Aggregated attribute** e.g., Aquatic ecotoxicity (related to pesticide *and* non-pesticide inputs)
1	much worse	much worse	much worse
2	much worse	worse	much worse
3	much worse	similar	worse
4	much worse	better	similar
5	much worse	much better	similar
6	worse	much worse	much worse
7	worse	worse	worse
8	worse	similar	similar
9	worse	better	similar
10	worse	much better	similar
11	similar	much worse	worse
12	similar	worse	similar
13	similar	similar	similar
14	similar	better	similar
15	similar	much better	better
16	better	much worse	similar
17	better	worse	similar
18	better	similar	similar
19	better	better	better
20	better	much better	much better
21	much better	much worse	similar
22	much better	worse	similar
23	much better	similar	better
24	much better	better	much better
25	much better	much better	much better

Five rating classes were applied for the two sub-attributes and the aggregated attribute (much worse, worse, similar, better, much better in relation to a baseline system). If equal weights are not used for the sub-attributes, the decision rules will differ from the example in this table.

Table 2 Example for sustainability rating of three apple protection systems

No.	Attribute	Advanced System (AS)	Innovative system (IS)
1	*Ecological-economic overall sustainability*	similar	similar
2	*Ecological sustainability*	similar	**better**
3	*Resource use*	similar	similar
4	Energy use per ha (LCA)	similar	similar
5	Land use (LCA)	similar	similar
6	Water use per ha (LCA)	similar	similar
7	Mineral resource use per ha (LCA)	similar	similar
8	*Environmental quality*	similar	**better**
9	Ecotoxicity	better	**much better**
10	Terrestrial ecosystem quality	better	**much better**
11	Terrestrial ecotoxicity potential (LCA)	much better	much better
12	Terrestrial ecotoxicity pesticide (LCA)	much better	much better
13	Terr. ecotoxicity non-pesticide (LCA)	much better	**better**
14	Terrestrial risk (Synops)	similar	**much better**
15	Acute terrestrial risk (Synops)	similar	**much better**
16	Chronic terrestrial risk (Synops)	similar	**better**
17	Aquatic ecosystem quality	better	**much better**
18	Aquatic ecotoxicity potential (LCA)	better	**much better**
19	Aquat. ecotox. pot. pesticide (LCA)	much better	much better
20	Aquat. ecotox. pot. non-pesticide (LCA)	similar	**much better**
21	Aquatic risk (Synops)	better	**much better**
22	Acute aquatic risk (Synops)	better	**much better**
23	Chronic aquatic risk (Synops)	better	**much better**
24	Impact on beneficial organisms	similar	**better**
25	Gobal warming potential (LCA)	similar	similar
26	Global eutrophication potential (LCA)	similar	similar
27	*Human toxicity (LCA)*	better	better
28	Human toxicity pesticide (LCA)	much better	much better
29	Human toxicity non-pesticide (LCA)	similar	similar
30	Economic sustainability	similar	similar
31	*Profitability*	worse	**similar**
32	Family income per labour hour	worse	**better**
33	Total production cost per kg 1st class fruit	similar	similar
34	Net profit per ha	worse	**similar**
35	*Production risk*	similar	**better**
36	Income variability	worse	**similar**
37	Probability of dramatic yield loss	similar	**much better**

38	*Financial autonomy*	similar	similar
39	Invested capital per ha	similar	**worse**
40	Return on investment per ha	worse	**similar**

Differences in the rating classes between AS and IS are in bold print. The following five rating classes were used to compare AS and IS with a baseline system (BS): much worse/ worse/ similar/ better/ much better. The sub-attributes were assumed to have equal weight.