A multicriteria decision method assessing the overall sustainability of new crop protection strategies: the case of apple growing in Europe

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Abstract: *Apple crop protection mainly relies on pesticides although several alternative pest management strategies being available. This is largely caused by the problem that multiple environmental and economic aspects are to consider simultaneously, hiding if one strategy is more sustainable than another. In our study we investigated the elements that need to be considered in order to reach transparency upon the overall result of the sustainability assessment. We present a system description tool created specially for data collection required by life cycle assessment, environmental risk assessment and full cost calculations. Using the various results from these assessments as qualitative attributes we designed a multicriteria tool that allows us to aggregate sustainability attributes over five levels to an overall sustainability rating. An example, assessing different crop protection systems of apple production, demonstrates the transparency of this method. We conclude that rating scales and decision rules might substantially influence the overall sustainability rating. Therefore, the definition of rating scales and decision rules should be carefully set and discussed among the research teams. In our case experts have participated from five European countries being partner of the EU-FP6 project ENDURE.*

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 relying on chemical pesticides (ENDURE, 2009). All members of the EU will have to propose a national action plan in order to implement IPM strategies adapted to regional conditions. Therefore methods and tools to evaluate the overall sustainability of such region-based IPM strategies are needed, though rarely available. 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 beside environmental also socio-economic aspect are provided by the approach of response induced sustainability evaluation RISE (Grenz et al., 2009) and the concept of sustainability solution spaces (Wiek and Binder, 2005; Castoldi et al., 2007). However, these tools do not attempt to aggregate the various aspects of sustainability to a rating of the overall sustainability of a system. Multi-attributive decision making offers a methodological framework suitable to define hierarchical trees of attributes that build up a rating for an overall sustainability (Bockstaller et al., 2008; Sadok et al., 2009). This is demonstrated by Bohanec et al. (2008) applying a multi-attribute model for economic and ecological assessment of genetically modified crops whereas Lô-Pelzer et al. (2009) evaluated innovative crop protection strategies for arable production systems. All these multi-attributive studies have in common that they allow for reflecting the complexity of agricultural system adequately. The number of attributes used in these models is very high, usually 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-effect relations in such models. Transparency should be enhanced. The goal of this paper is to investigate the methodological elements that need to be considered in order to reach transparency upon the overall result of a sustainability assessment. An example demonstrates the transparency of this method while applying it to assess different crop protection systems of apple production. Rating scales and decision rules used in the sustainability assessment were defined by a group of experts participating in the EU-FP6 project ENDURE.

Scheme for sustainability evaluation

We propose a scheme for sustainability assessment of orchard systems that includes five elements. Starting point is the description of the farming systems with parameters (Fig. 1, a). 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. 1, b). The diverse output variables of the assessments are then entered at the bottom of a hierarchical attribute tree as the so called basic attributes (Fig. 1, c). Here the quantitative results are transformed into qualitative ratings in order to aggregate them into attributes of higher levels (Fig. 1, d). Since in our project we apply the multicriteria method to evaluate crop protection systems, the rating of the overall sustainability is the main result. However, for optimising crop protection systems we need to know which parameters of the system description influence a certain overall sustainability evaluation result. Such cause-effect relations can be easily obtained by investigating the results top-down in the proposed scheme in Fig. 1.

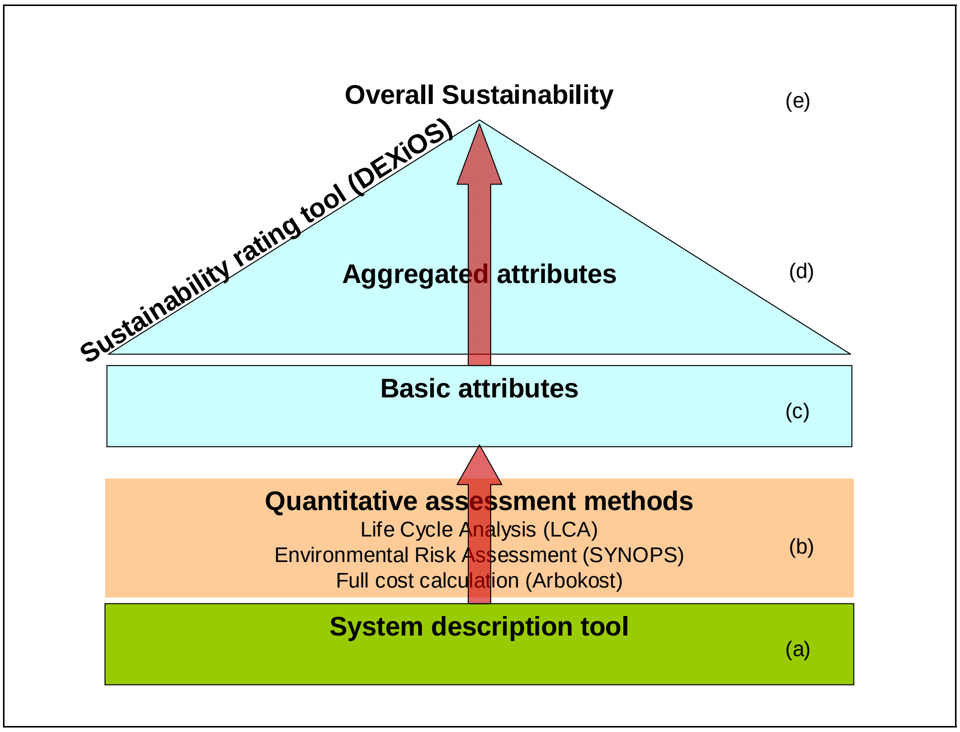

Figure 1. Scheme for assessing the overall sustainability of orchard systems.

System description tool

Our study focuses on defining crop protection strategies with reduced ecotoxicity compared to a Baseline System (BS) that relies strictly on chemical pest control. We distinguished therefore an advance system (AS) that replaces chemical pesticides as far as possible by alternative methods that are available on the market and an innovative system (IS) replacing chemical pesticides by alternative methods that are used in field trials or laboratories at the moment. Thus the system description needs to reflect in detail the level of direct crop protection telling which active ingredients were used, which dosage was applied and in which calendar week the application was held. Such definitions need to be related to expected yield levels. It turned out that for experts it is practicable to follow the target yield concept (Bera et al., 2006). The target approach takes in consideration the efficiency of crop protection parameters for attending desired target parameters 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 into context and target parameters in our system description tool. By keeping context and target parameters for a region constant we were able to compare the sustainability of different crop protection strategies (i.e. AS and IS) while assessing the whole farming system.

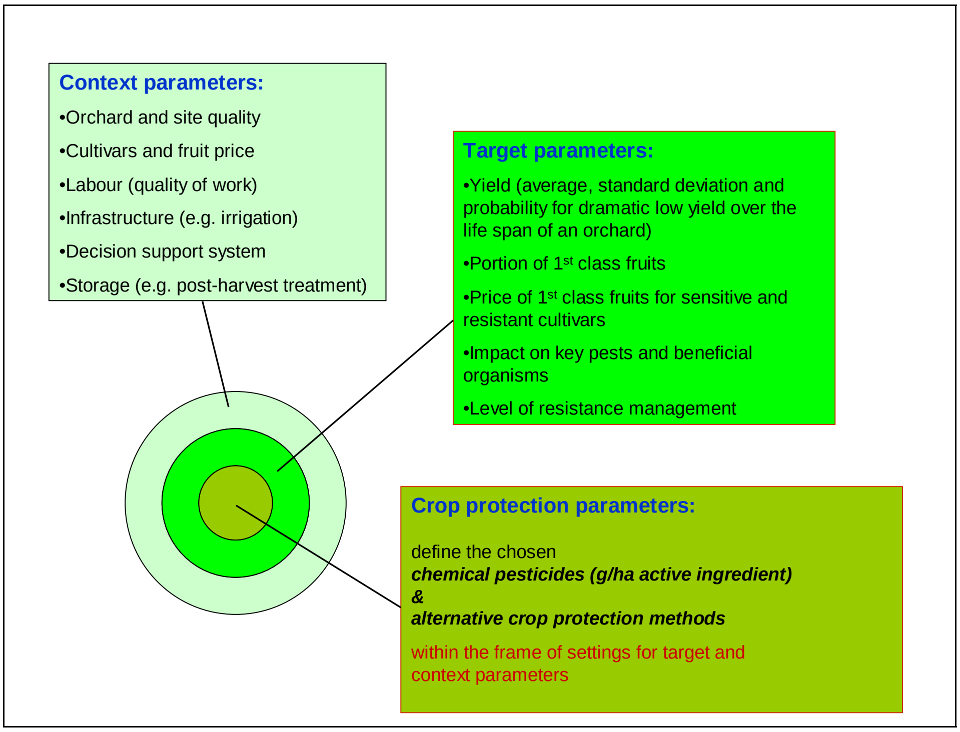

Figure 2. Three types of system description parameters for defining crop protection strategies for apple production.

Quantitative assessment methods

Life cycle assessment

The design of a LCA study is outlined in ISO 14044 (ISO, 2006). Values from system description parameters (Fig. 2) defining crop protection systems for apple orchards are transformed into the life cycle inventory which is used in the impact assessment to evaluate the environmental effects. The boundary of the system is set at harvest and does not include post harvest processes like storage. The system includes all inputs like fertiliser and machinery and processes (e.g. operation of machines). We use 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 assessment models are described in the SALCA method (Gaillard and Nemecek, 2009; Nemecek et al., 2005, 2008) to estimate the various direct field emissions (i.e. NH_3, N_2O, Phosphorus, NO_3-, heavy metals and pesticides). Referring to the basic attributes related to LCA (Fig. 3) the following methods are applied:

- Demand for non-renewable and renewable energy resources (Hischier et al., 2009)
- Global warming potential over 100 years (IPCC, 2006)
- Terrestrial and aquatic eco-toxicity potential (Guinée et al., 2001)
- Human toxicity potential (Guinée et al., 2001)
- Eutrophication potential (Hauschild & Wenzel, 1998)

SYNOPS

The indicator model SYNOPS assesses the risk potential for terrestrial (i.e. soil and field margin biotopes) and aquatic (i.e. surface water) organisms caused by the application of plant protection products (PPM). It combines use data of PPM's with the environmental conditions linked to the application and the chemical, physical and eco-toxicological properties of the applied active ingredients (Gutsche and Strassemeyer, 2007).

In general the acute and chronic risk potentials are calculated as exposure toxicity ratios (ETR) for reference organisms in the three compartments soil, surface water and field margin biotopes. These organisms are earthworms for soil, bees for edge-biotopes and daphnia, algae and fish for surface water. SYNOPS estimates for each application the loads of an active ingredient into the soil, edge-biotopes and surface water considering the exposure pathways drift, run-off, and drainage. Based on the estimated loads of active ingredients a time dependent curve of the predicted environmental concentration (PEC) is derived assuming a temperature dependent degradation of the active ingredients. From the time dependent concentration curves the acute and chronic risk potentials are derived by relating the maximum PEC values to lethal concentration (LC50) and the no effect concentration (NOEC).

All necessary physico-chemical and eco-toxicological parameters of the applied active ingredients (n = 400) are summarised in a database, which were derived mainly from the monographs produced as part of the review process on EU or national level. The region specific field related and environmental conditions like slope, soil type and climate data were derived from a spatial database which was developed within the EU-Project HAIR (2007).

Full cost calculation

Orchard systems are capital (e.g. establishment costs) and labour intensive (e.g. harvest hours) production systems with a live span of 10 to 15 years. Income may vary considerably between the years mainly depending on variability of yield and portion of 1st class fruits (Mouron et al., 2007). Thus, the economic assessment highlights the average profitability, the financial autonomy as well as the income risk. Crop profitability evaluates the economic efficiency of the orchard systems by calculating the family income per labour hour, the total production cost per kilogramme 1st class apples as well as the net profit per hectare. Farm autonomy is represented by the amount of invested capital per hectare and the return on investment since they evaluate the grower's capacity to amortise or reinvest and therefore refer to the viability in the long run. Production risk is represented by calculation of the income variability due to the standard deviation of yield and fruit quality over the life span of the orchard. Furthermore, the income risk is considered by estimating the portion of years with a dramatic yield loss, i.e. years with less than half of the average harvest.

Full cost principles are applied. The calculations are conducted by utilising the managerial-economic software-tool Arbokost (Arbokost, 2009). This full cost calculation tool is designed especially for perennial crops. It had been created by the Swiss research station Agroscope Changings-Wädenswil.

Sustainability rating tool

Building a hierarchical attribute tree

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

The sub-attributes for *Economic sustainability* are *Profitability, Production risk* and *Autonomy* according to Lô-Pelzer et al. (2009). From bottom-up the basic ecological attributes were given by the result parameters of the Life Cycle Assessment respectively the SYNOPS assessment. Since the rating of ecotoxicology is the focus of our study this attribute is represented with the most sub-attributes providing detailed information on how the ecotoxicity is influenced. The basic attributes referring to economic sustainability of orchard systems were selected with regard to previous studies (Mouron et al., 2001, 2007; Bravin et al., 2010).

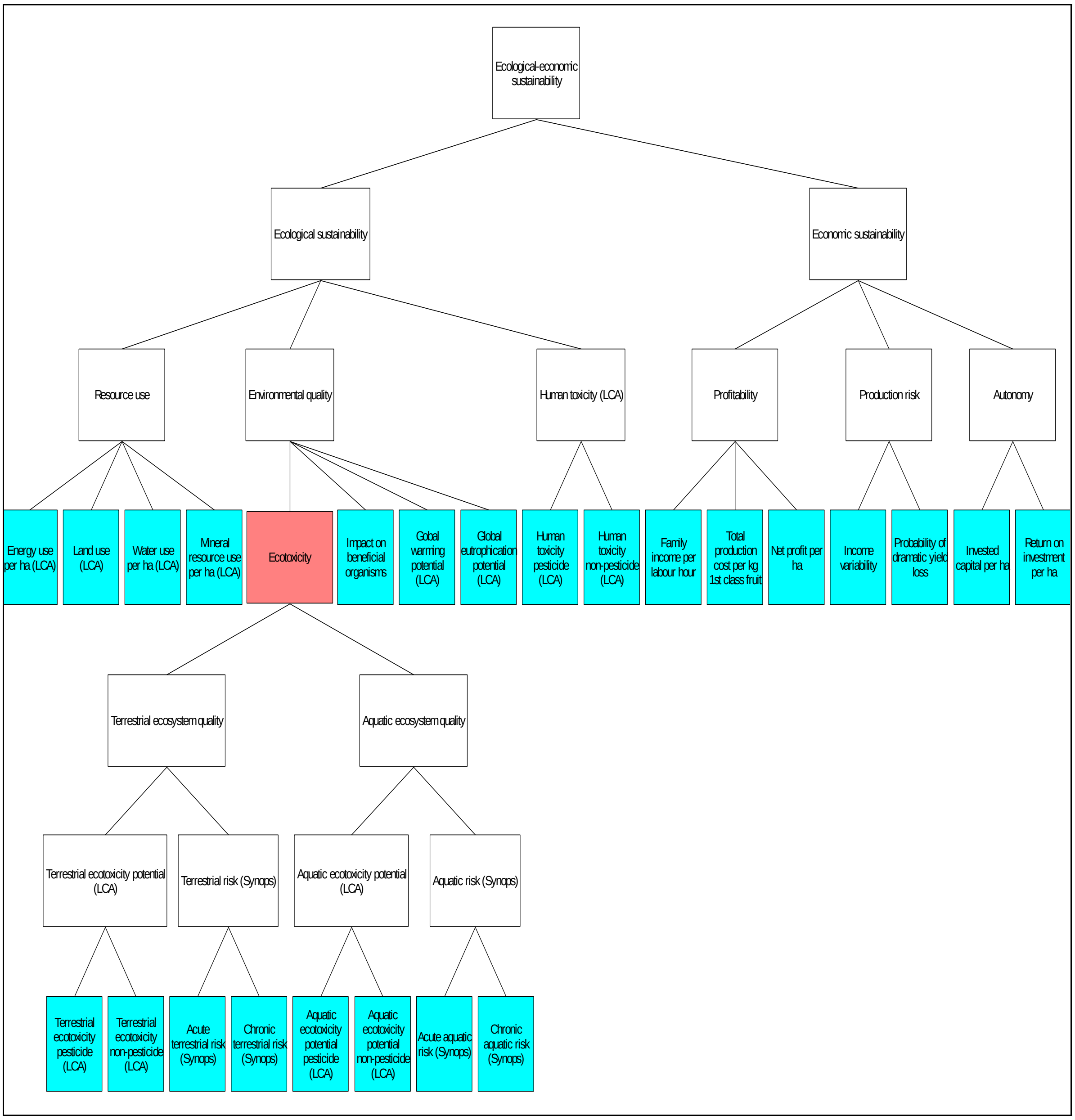

Figure 3. Hierarchical attribute tree for assessing the ecological and economic sustainability of orchard systems; basic attributes are in blue print; the attribute being optimised is in red print.

Rating basic attributes

The numeric values derived from the assessment methods need to be rated indicating if the result differs substantially from a Baseline System (BS). Table 1 shows the five relative classes used for rating basic and aggregated attributes.

Table 1. Classes for rating basic attributes.

Rating classes	Description used in DEXiOS
much worse than Baseline System	much worse
worse than Baseline System	worse
similar to Baseline System	similar
better than Baseline System	better
much better than Baseline System	much better

Basic attributes with strictly positive numeric values need a rating scale which prevents the change of the rating by a shift of the reference system (i.e. BS). Therefore the boundary between similar and better is the reciprocal of the ones between similar and worse as well as the one between better and much better is the reciprocal of the boundary 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 classes related to ecotoxicity and human toxicity are wider as for nutrient and resource management reflecting that methodologies for assessing ecotoxicity are less reliable than those for nutrition and resource assessments.

For basic attributes with possibly negative or positive numeric values which are *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%) to the desired side is of the same relative effect as it is to the undesired side. Example for a symmetric rating scale: 90 % -110 % = similar to BS; better than BS = 110 % - 140 %; worse than BS = 60 % - 90 %

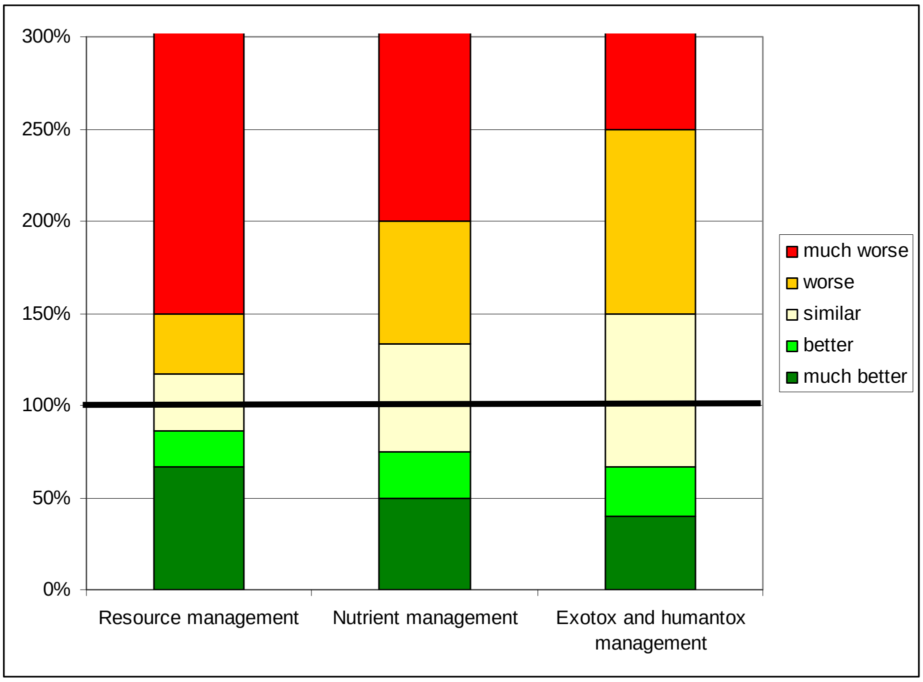

Figure 4. Asymmetric scales for rating Life Cycle Assessment results in relation to a Baseline System (= 100 %).

Rating aggregated attributes

Decision rules are the components of multi-attribute models that define the aggregation aspect of option evaluation and therefore map all the combinations of sub-attribute values into the values of the aggregated attribute (Bohanec et al., 2008). Each aggregate attribute in the model (Fig. 3) has an associated set of rules that carry out such a mapping. In principle, the rules represent attitudes and preferences of the decision maker; in our case the rules have been specified jointly by experts from five European countries, who are partners of the EU-FP6 project ENDURE.

Tab. 2 shows an example of decision rules that aggregate two sub-attributes (*Aquatic ecotoxicity potential pesticide* and *non-pesticide*, respectively) into an aggregate attribute (*Aquatic ecotoxicity potential*). Here, all the three attributes have the same five classes from Tab. 1. In this case, the two sub-attributes contribute equally to the aggregate attribute; consequently, they are of equal importance and have equal weights, and the decision rules are symmetric with respect to the sub-attributes. Individual decision rules are shown in Tab. 2. If the two sub-attributes do not differ in their classes, the aggregated attribute will have the same class as its sub-attributes (Tab. 2, No. 1, 7, 13, 19, 25). If the difference comes to two or four classes, the aggregated attribute will get the class situated in between of the ones of the sub-attributes (Tab. 2, No. 3, 5, 9, 11, 12, 15, 17, 21, 23). In all other cases, the aggregation is as shown in Tab. 2, No. 2, 4, 6, 8, 10, 14, 16, 18, 20, 22, 24.

Table 2. Decision rules for rating aggregated attributes with equal weights.

Decision rule number (No.)	**Sub-attribute 1** (e.g. Aquatic ecotoxicity potential pesticide)	**Sub-attribute 2** (e.g. Aquatic ecotoxicity potential non-pesticide)	**Aggregated attribute** (e.g. Aquatic ecotoxicity potential)
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

The same five rating classes are applied for the two sub-attributes and the aggregated attribute. If it is decided not to use un-equal weights for the sub-attributes, the decision rules will differ from the one of this table.

Example for an overall sustainability rating

We compared different crop protection systems for apple production under European conditions aiming to reduce ecotoxicity. Therefore we defined a Baseline System (BS), an Advanced System (AS) and an Innovative System (IS). The BS operates only with chemical pesticides within the frame of good agricultural practice. The AS aims to replace chemical pesticides as far as possible by alternative methods available on the market and the IS has the same goal but uses also alternative methods which are currently used in field trials and will be approximately on the market within 10 years. AS and IS are considering integrated production principles. 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 utilised the above described hierarchical attribute tree (Fig. 3), rating classes (Tab. 1), rating scales (Fig. 4) and decision rules (example in Tab. 2). The resulting ratings for the 40 attributes are presented in Tab. 3. It demonstrates that in this example the Ecological-economic overall sustainability (attribute No. 1) did not differ substantially neither for AS nor for IS indicated by the rating class "similar" (i.e. similar to BS). This might be surprising since AS and IS reduced considerably the applications of chemical pesticides compared to BS. We can now easily investigate the reasons for this outcome. First of all the rating of the attribute *Ecotoxicity* (Tab. 3, No. 9) has been improved as expected, in case of the AS for one rating class and for IS for two classes. This is mainly due to improvements among the sub-attributes of *Ecotoxicity* (i.e. attribute No. 10 – 23). However, one level higher in the attribute tree the *Environmental quality* (Tab. 3, No. 8) for the AS is rated similar to BS. This is caused by the ratings of the three sub-attributes of *Environmental quality*, namely *Impact on beneficial organisms*, *Global warming potential* and *Global eutrophication* (Tab. 3, No. 24 – 25). *Environmental quality* contributes together with *Resource use* and *Human toxicity* to the top attribute of the environmental branch of the tree which is called *Ecological sustainability* (Tab. 3, No. 2). On this level the AS remains similar to BS and IS gets a one class better rating. Together with the rating from the top attribute of the economic branch, i.e. *Economic sustainability* (Tab. 3, No. 30), it is clear that the AS got the rating "similar" for the overall sustainability, since both sub-attributes were rated with "similar". In case of IS one related sub-attributes was rated with "similar" the other with "better". According to the decision rules of Tab. 2 the aggregated rating will then be "similar". We like to point out that the decision rules of Tab. 2 reflect just the preference we have chosen 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 to aggregate different attributes.

Table 3. Example for sustainability rating of different crop protection systems for apple production.

No.	Attrributes	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	Terrestrial 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	Aquatic ecotoxicity potential pesticide (LCA)	much better	much better
20	Aquatic ecotoxicity potential 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	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 are applied comparing the AS and IS with a Baseline System: much worse/ worse/ similar/ better/ much better; equal weights for sub-attributes are assumed.

Conclusions

The result of a multi-attributive sustainability assessment might be substantially different depending on definitions and settings of several elements. In order to reach transparency on the assessment results we identified the following tasks:

1. A well structured system description tool is the base for keeping the attribute tree slim. Defining crop protection parameters in relation to fixed context and target parameters helps to interpret the outcome of the assessment.
2. Applying established assessment methods such as Life Cycle Assessment insures that quantitative analysis is based on the state of the art method. Models underlying these calculations are therefore clearly described including awareness of uncertainty.

3. In order to translate quantitative assessment results into qualitative rating classes, asymmetric scales need to be defined if the numeric result can not be below zero. The definition of scales might substantially influence the overall sustainability rating.
4. The rating of aggregated attributes depends on decision rules since certain combinations of sub-attribute ratings might be interpreted differently according to subjective preferences. Thus, decision rules might substantially influence the overall sustainability rating as well.

We suggest that these four tasks should be defined within research teams. In our case experts from five European countries being partner of the EU-FP6 project ENDURE have participated in the study.

References

Arbokost (2009) *Betriebswirtschaftliches Simulationsprogramm*. Agroscope Changins Wädenswil. *www.arbokost.info-acw.ch.*

Bera, R., Seal, A., Bhattacharyya, P., Das, T.H., Sarkar, D. and K. Kangjook (2006) Target yield concept and a framework of fertilizer recommendation in irrigated rice domains of subtropical India. *Journal of Zhejiang University SCIENCE B, 7 (12): 963-968.*

Bockstaller, C., Guichard, L., Makowski, D., Aveline, A., Girardin, P. and S. Plantureux (2008) Agri-environmental indicators to assess cropping and farming systems. A review. *Agronomy for Sustainable Development 28(1): 139-49.*

Bohanec, M. (2009) DEXi: A Program for Multi-Attribute Decision Making. *http://www-ai.ijs.si/MarkoBohanec/dexi.html*

Bohanec, M., Messean, A., Scatasta, S., Angevin, F., Griffiths, B., Krogh, P.H., Znidarsic, M. and S. Dzeroski (2008) A qualitative multi-attribute model for economic and ecological assessment of genetically modified crops. *Ecological Modelling 215(1-3): 247-61.*

Bravin, E. and A. Kilchenmann (2010) Ländervergleich der Apfelproduktion. *Agrarforschung Schweiz 1(2): 52-59.*

Castoldi, N., Bechini, L., Steinberger J. and C. Binder (2007) *Sustainability Solution Space using agro-ecological indicators at field level.* Presentation held at Farming Systems Design 2007, Catania, Italy, September 10-12.

ENDURE (2009) Interview with Pierre Ricci ENDURE coordinator. *http://www.endure-network.eu/about_endure/all_the_news/interview_pierre_ricci_endure_coordinator*

Foster, C., Green, K., Bleda, M., Dewick, P., Evans, B., Flynn, A. and J. Mylan (2006) *Environmental impacts of food production and consumption: A report to the Department for Environment, Food and Rural Affairs.* Manchester Business School. Defra, London.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, G., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M. and G. Wernet (2007) *Overview and Methodology. Swiss Centre for Life Cycle Inventories*. Dübendorf, ecoinvent report.

Gaillard, G. and T. Nemecek (2009) Swiss Agricultural Life Cycle Assessment (SALCA): *An integrated environmental assessment concept for agriculture.* In: Int. Conf. "Integrated Assessment of Agriculture and Sustainable Development, Setting the Agenda for Science and Policy", Egmond aan Zee, The Netherlands. AgSAP Office, Wageningen University, 134-135.

Grenz, J., Thalmann C., Stämpfli A., Studer, C. and F. Häni (2009) RISE – a method for assessing the sustainability of agricultural production at farm level. *Rural Development News 1/2009.*

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, H., van Duin, R., Huijbregts, M.A.J., Lindeijer, E., Roorda, A.A.H. and B.P. Weidema (2001) *Life cycle assessment - An operational guide to the ISO standards*. Ministry of Housing, Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML), Den Haag and Leiden, Netherlands

Gutsche, V. and J. Strassemeyer (2007) *SYNOPS - ein Modell zur Bewertung des Umwelt-Risikopotentials von chemischen Pflanzenschutzmitteln*. Institut für Folgenabschätzung im Pflanzenschutz, Biologische Bundesanstalt für Land- und Forstwirtschaft.

HAIR (2007) GIS related database. http://www.rivm.nl/rvs/risbeoor/Modellen/Results_of_HAIR_project.jsp

Hauschild, M.Z. and H. Wenzel (1998) *Environmental assessment of products.* Vol. 2: Scientific background. 2. Chapman & Hall, London. 565 p.

Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Frischknecht, R. Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerinick, Y., Margni, M.m and T. Nemecek (2009) *Implementation of Life Cycle Impact Assessment Methods, Datav2.1*. Swiss Centre for Life Cycle Inventories, Dübendorf, ecoinvent report.

IPCC (2006) *IPCC guidelines for national greenhouse gas inventories.* Volume 4: Agriculture, forestry and other land use. Kanagawa, Simon Eggleston, L.B., Kyoko Miwa, Todd Ngara and Kiyoto Tanabe.

ISO (2006) *ISO 14044, 1st Edition, - Environmental management - Life cycle assessment - Requirements and guidelines.* Geneva, 46 p.

Lô-Pelzer, E., Bockstaller, C., Lamine, C., Mouron, P. and A. Messéan (2009) *DEXi-PM: a model for ex ante sustainability assessment of innovative crop protection strategies.* Presentation held at Farming System Design, Monterey (USA), 23-26 August 2009. http://www.endure-network.eu/about_endure/ all_the_news/dexipm_assessing_cropping_system_sustainability

Mila i Canals, L., Cowell, S.J., Sim, S. and L. Basson (2007) Comparing domestic versus imported apples: A focus on energy use. *Environmental Science and Pollution Research 14(5): 338-44.*

Mouron, P., and D. Carint (2001) Rendite-Risiko-Profil von Tafelobstanlagen. *Schweiz. Z. Obst-Weinbau 137, 78 – 81, Wädenswil.*

Mouron, P. and R. W. Scholz (2007) Management Influence on Income Risk in an Apple Production System on Swiss Fruit Farms. *International Journal of Fruit Science 7 (4): 47 – 70.*

Mouron, P., Nemecek, T., Scholz, R.W. and O. Weber (2006a) Management influence on environmental impacts in an apple production system on Swiss fruit farms: Combining life cycle assessment with statistical risk assessment. *Agriculture Ecosystems & Environment 114(2-4): 311-22.*

Mouron, P., Scholz, R.W., Nemecek, T. and O. Weber (2006b) Life cycle management on Swiss fruit farms: Relating environmental and income indicators for apple-growing. *Ecological Economics 58(3): 561-78.*

Nemecek, T. and S. Erzinger (2005) Modelling Representative Life Cycle Inventories for Swiss Arable Crops. *Int J LCA 10(1): 68-76.*

Nemecek, T. and T. Kägi (2007) *Life Cycle Inventories of Swiss and European Agricultural Production Systems.* Final report ecoinvent V2.0 No. 15a, Agroscope Reckenholz-Taenikon Research Station ART, Swiss Centre for Life Cycle Inventories, Dübendorf, ecoinvent report.

Nemecek, T., Huguenin-Elie, O., Dubois, D. and G. Gaillard (2005) *Ökobilanzierung von Anbausystemen im schweizerischen Acker- und Futterbau.* Schriftenreihe Nummer 58, Agroscope ART Zurich, pp. 53-59.

Nemecek, T., von Richthofen, J.-S., Dubois, G., Casta, P., Charles R. and H. Pahl (2008) Environmental impacts of introducing grain legumes into European crop rotations. *European Journal of Agronomy 28(3): 380-393.*

Sadok, W., Angevin, F., Bergez, J.E., Bockstaller, C., Colomb, B., Guichard, L., Reau, R., Messean, A. and T. Dore (2009) MASC, a qualitative multi-attribute decision model for ex ante assessment of the sustainability of cropping systems. *Agronomy for Sustainable Development 29(3): 447-61.*

Udo de Haes, H. and E. Lindeijer (2002) The conceptual structure of life-cycle impact assessment. In: Udo de Haes, H., Finnveden, G., Goedkoop, M., Hauschild, M., Hertwich, E.G., Hofstetter, P., Klöpffer, W., Krewitt, W., Lindeijer, E.W., Mueller- Wenk, R., Olson, S.I., Pennington, D.W., Potting, J. and B. Steen (eds.) *Life-cycle impact assessment: Striving towards best practice.* SETAC Press, pp. 209-225.

Wiek, A. and C. Binder (2005) Solution spaces for decision-making – a sustainability assessment tool for city-regions. *Environmental Impact assessment Review 25: 589-608*.