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# Conceptual and case study multi criteria sustainability assessment of dairy mix farming systems

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# Conceptual and case study multi criteria sustainability assessment of dairy mix farming systems

Par : Marie CALVEZ



**Soutenu à RENNES le 27 / 06 / 2024**

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*Les analyses et les conclusions de ce travail d'étudiant n'engagent que la responsabilité de son auteur et non celle de l'Institut Agro Rennes-Angers et l'université de Rennes 1*

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# Conceptual and case study multi criteria sustainability assessment of dairy mix farming systems

DairyMix project: upgrading DEXi trees & Polish farm case study report

<b>1 INTRODUCTION.....</b>	<b>7</b>
1.1 Current agriculture’s impacts forcing a changeover.....	7
1.2 Development of tools and frame of analysis to assess sustainability.....	9
1.3 DairyMix, the european project frame of the internship.....	13
<b>2 MATERIAL AND METHODS.....</b>	<b>17</b>
2.1 Methods for Multi Criteria Assessment.....	17
2.1.1 DEX method.....	17
2.1.2 Finalisation of DEXi-DairyMIX-1-tree based on 3 sustainability dimensions...	19
2.1.3 DEXi-DairyMIX-2-tree based on sustainability properties.....	23
2.2 Case study farms and data collection.....	23
2.3 Calculation of indicator from LCA assessment.....	25
2.3.1 Definition of the assessed system and objectives.....	25
2.3.3 Impact analysis with Simapro ®.....	27
2.4 Calculation of indicators that do not depend on LCA.....	27
<b>3 RESULTS.....</b>	<b>29</b>
3.1 First DEXi tree.....	29
3.2 Second DEXi tree new conceptual assessment framework.....	31
3.3 LCA assessment of Polish farms.....	35
3.4 AMC Environmental and social assessment of Polish farms with DEXi-1 tree.....	37
Polish Farms Comparaison with French farms.....	37
<b>4 DISCUSSION AND PROSPECT.....</b>	<b>39</b>
<b>5 CONCLUSION.....</b>	<b>45</b>
<b>Bibliography references:.....</b>	<b>46</b>
<b>Appendix.....</b>	<b>51</b>

## List of Figures

Figure 1 : Estimated contribution of agriculture in the impact on the earth system in the 9 planetary boundaries frame of analysis (Campbell et al. 2017).....	5
Figure 2 : Futur plausible for agroecological agriculture in Europe TYFA scenario (Poux & Aubert, 2018).....	5
Figure 3 : Generic workflow and applications of an LCA (EU JRC, 2022).....	7
Figure 4 : Organisation of the different work packages in the DairyMix project.....	13
Figure 5 Illustration of the missions presented in this report and their integration in the DairyMix project.....	13
Figure 6 : Organization of the hierarchical multi attribute DEXi model with a theoretical example.....	15
Figure 7 Social and Economical branches of the DEXi-1-tree.....	17
Figure 8 : Environmental branch of the DEXi-1-tree.....	19
Figure 9 : DEXi-2-tree provision and viability branches.....	29
Figure 10 : DEXi-2-tree Efficiency & sobriety and Resilience branches.....	31
Figure 11 : DEXi-2-tree Autonomy branch.....	33
Figure 12 Impact categories of LCA analysis.....	33
Figure 13 : Radar graph, result of the sustainability assessment at sub branch level for environmental and social dimensions.....	35
Figure 14 : Result of the DEXi-1-tre assessment of social branch versus environmental branch for the 2 Polish and 3 French farms .....	35

## List of Tables

Table 1 : Characteristics sought in existing assessment tools to test their suitability for our objective.....	11
Table 2 : Main characteristics of Polish farms.....	23
Table 3 : Weightings of environmental branch for Poland and France.....	27

## Glossary

DairyMix : Name of the international project to assess Mix Dairy farms sustainability in Europe and Argentina

DPS: Dairy Production Systems

FAO : Food and Agriculture Organisation of the United Nations

FPCM : Fat and Protein Corrected Milk, functional unit considered for the Multicriteria assessment method and the LCA analysis

GHG : Greenhouse gas emissions

INRAE : French National Research Institute for Agriculture, Food and the Environment (Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement)

LCA : Life Cycle Assessment

MCA: Multi Criteria Analysis

Simapro ® : Software used to perform Life Cycle Assessment

TFI: Treatment Frequency Index

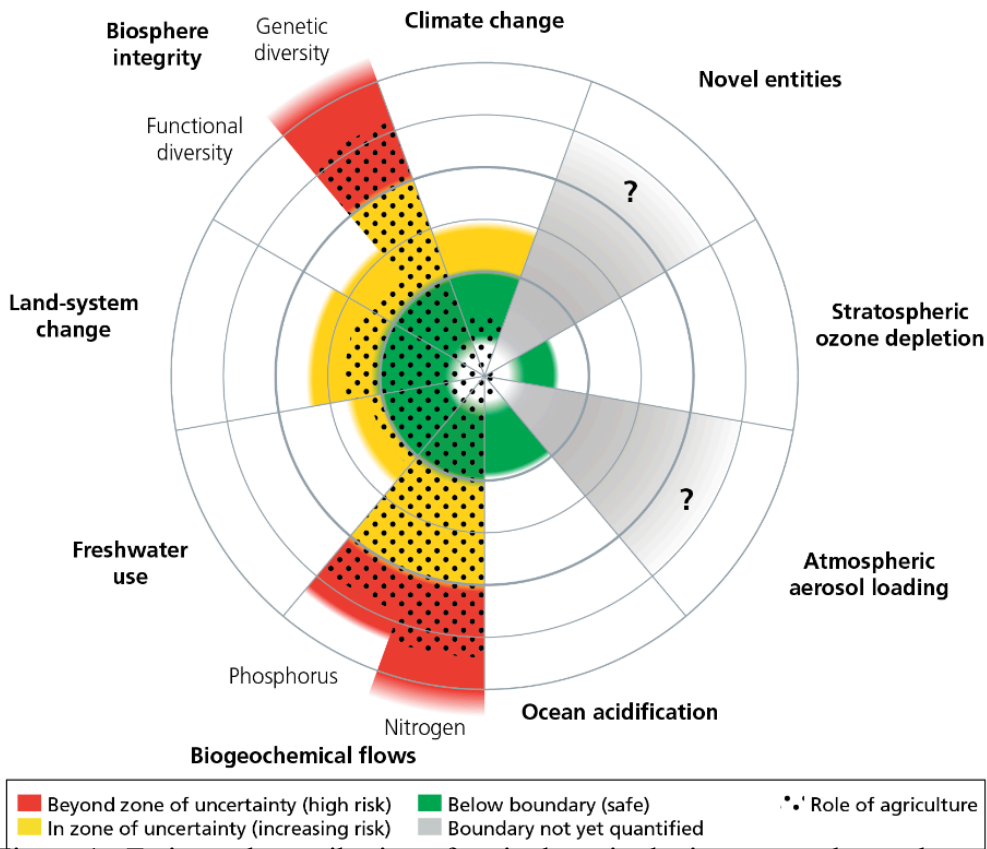


Figure 1 : Estimated contribution of agriculture in the impact on the earth system in the 9 planetary boundaries frame of analysis (Campbell et al. 2017).

## TYFA : A SCENARIO FOR AN AGRO-ECOLOGICAL EUROPE IN 2050

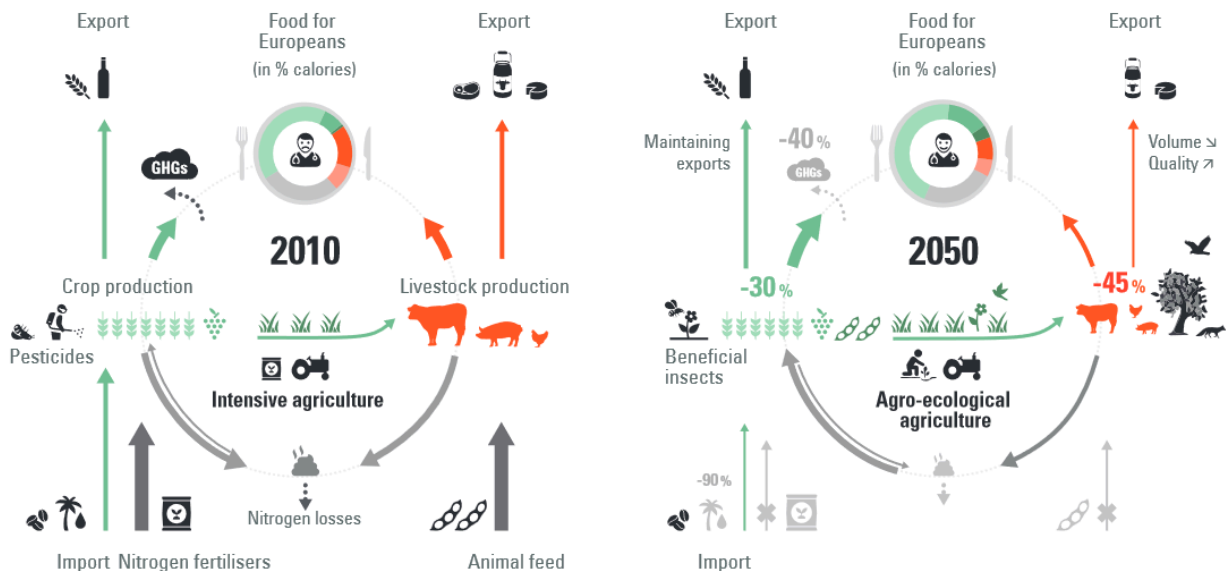


Figure 2 : Futur plausible for agroecological agriculture in Europe TYFA scenario (Poux & Aubert, 2018).

# 1 INTRODUCTION

## 1.1 Current agriculture's impacts forcing a changeover

Human societies development based on fossil fuels increased in a considerable way the pressure on the environment. Due to human activities, greenhouse gases (GHG) emissions have risen strongly and continue to rise, causing climate changes (IPCC, 2021). Geologists introduced the neologism 'Anthropocène' to emphasize that we are entering a geological era where human societies are the main drivers of environmental changes. To quantify anthropogenic impacts on earth systems, an assessment framework called 'planetary boundaries' has been introduced to highlight the main impacts at global scale (Rockström et al., 2009). This framework is based on 9 limits of the earth system, delineated as 'safe operating zones' for humanity. At that time, 3 limits—*climate change*, *biodiversity loss* and *biogeochemical flow for nitrogen*—over the 7 assessed surpassed the safe operating established limits. Subsequent assessments indicated that the second criteria of *biogeochemical flow (for phosphorus)* and *changes in land use* also exceeded the defined safe limits (Steffen et al., 2015). In the latest version where all boundaries are assessed, *novel entities* and *freshwater change* exceeded their respective boundaries, indicating that six of the nine boundaries now lie beyond safety margins (Richardson et al., 2023).

The planetary boundaries framework highlights that agriculture is a major driver of several critical environmental limits (Campbell et al., 2017). According to this analysis, among the limits estimated beyond the zone of uncertainty, *biosphere integrity* and *geochemical flows* are driven first by agriculture's negative impacts (**Figure 1**). Phosphorus and nitrogen nutrient losses from agriculture practices negatively affects terrestrial and aquatic ecosystems (Malagó & Bouraoui, 2023). For limits within the uncertainty zone, agriculture is also the main driver of *land-change systems*, *freshwater use* and is a significant contributor for *climate change*. Land use changes which lead to habitat fragmentation or destruction, and overexploitation are considered as the main drivers for biodiversity loss (Caro et al., 2022). And about climate change, the world agriculture sector contributes to 22% of global GHG emissions (Chapman et al., 2019). In 2001, Tilman et al. highlighted that the environmental impacts of agriculture may continue to increase if the current production system does not change (Tilman et al., 2001).

Livestock is often targeted for its ecological impact since livestock production systems account for 80% of agriculture GHG emissions, with beef and dairy systems estimated to account for 65% of livestock GHG emissions (Chapman et al., 2019). Same authors also recall that the first GHG emissions associated with animal production systems are methane and nitrous oxide.

One of the most widespread definitions of 'sustainable development' is the one proposed in Brundtland's Report i.e. "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN-WCED, 1987). To have an idea of what sustainable agriculture in Europe could look like, IDDRI-AScA institute performed a holistic transformation scenario to compare agriculture in 2010 and a possible one in 2050 based on agroecological production systems, illustrated in **Figure 2** (Poux & Aubert, 2018). In this study, hypotheses are made for every practice of the agricultural and food system: fertility management, plant production, land use, animal production, non-food uses and European diets. This ambitious model bans pesticide use by precautionary principle and mineral fertilizers. Therefore, it relies on fertility transfers



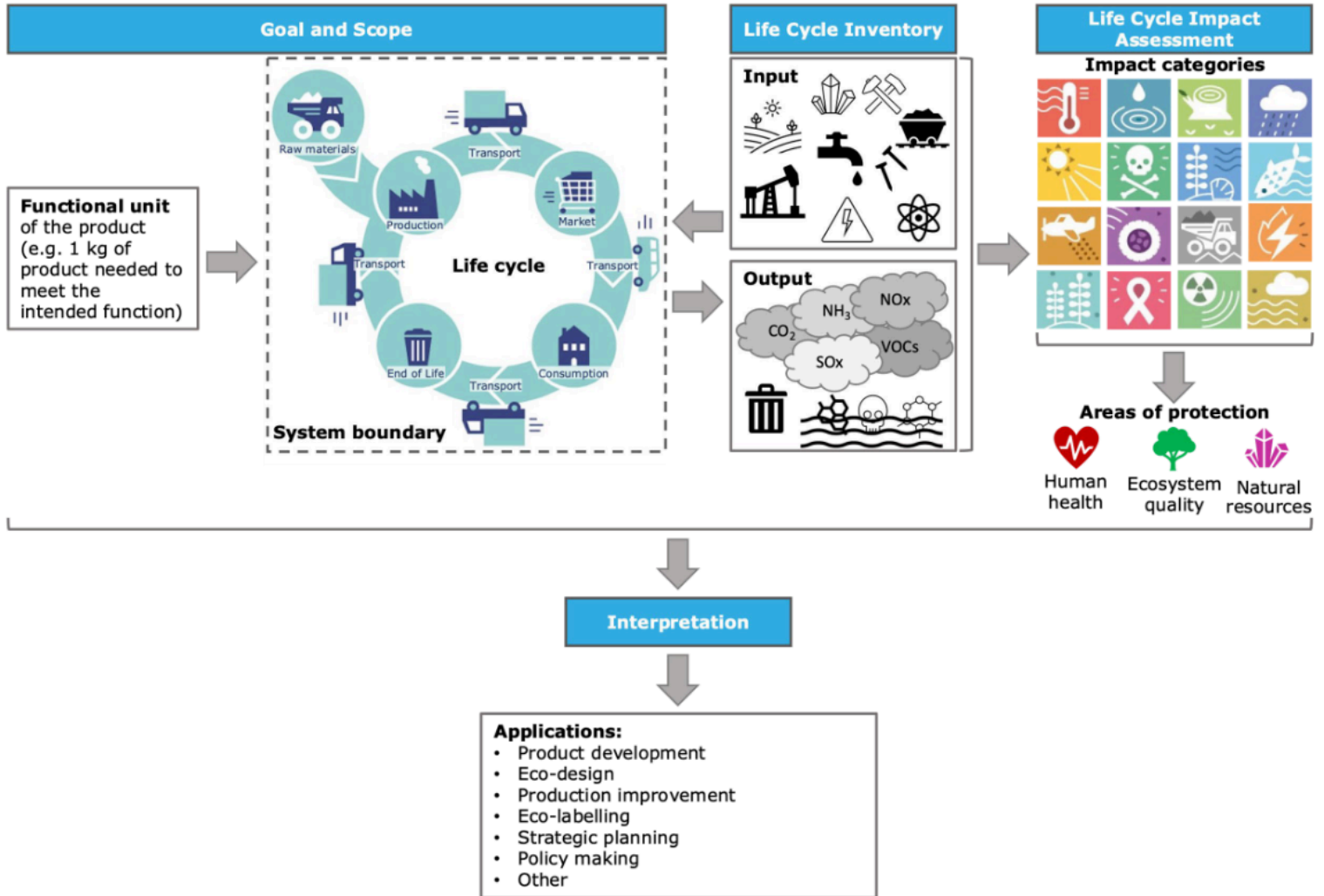


Figure 3 : Generic workflow and applications of an LCA (EU JRC, 2022)

between areas where leguminous crops grow and fix nitrogen to areas with non-leguminous crops. These transfers are made by livestock manure. Changes in livestock production are drastic : overall reduction in animal product consumption and export of animal products and extensification of livestock production. For dairy products: between 2010 and 2050 a decline by 31% is modeled but beef production stays the same, with an extensification of the grass-fed dairy production to be coherent with the maintenance and the development of permanent pastures to enhance biodiversity of European agriculture. This forecasting study is useful to underline the fundamental role of cattle production in sustainable food production systems that rely on agroecological principles. In this context, arise the interest of mixed farming production systems that conciliate the production of animal products such as milk and protein crops.

To develop new production systems more sustainable, we need to be able to assess their sustainability. Sustainability is often considered in an approach with 3 dimensions : economical, environmental and social. Then, numerous tools have been developed, to assess one or several dimensions of production systems more or less specialized.

## 1.2 Development of tools and frame of analysis to assess sustainability

### *Multi-Criteria Assessment*

To address the assessment needs from a holistic perspective, various Multi-Criteria Assessment (MCA) methods have been developed (Lairez et al., 2016) . Assessment tools are qualified as *ex post* or *ex ante* when they aim to assess respectively existing systems or future systems or scenarios. Indeed, the choice of indicator may not be the same because the available data to assess the system will not be the same. MCA tools rely on a series of indicators that can be classified depending on their type: *cause indicators* are predictive indicators which assess the cause, *consequence predictive* if they predict the effects or *consequence indicators* if they can directly measure the targeted phenomenon. Choice of indicators is not always an easy task, it's a compromise between less accurate but more easy to measure predictive indicators or more accurate but difficult or impossible to measure consequence indicators.

### *Life Cycle Assessment*

The Life Cycle Assessment (LCA) methodology stands out for evaluating the environmental impacts of a product or service throughout its entire life cycle (**Figure 3**). The widespread use of LCA can be attributed to several factors. Firstly, LCA is inherently holistic as it quantifies impacts from cradle to grave. Additionally, the principles and application of the method has been standardized through the ISO 14040 and ISO14044 norms (ISO, 2006), facilitating the establishment of a uniform and comparable framework. Previous LCA studies facilitate the comparative analysis of new results. It is the reference method for calculating environmental impacts, and has been used for environmental labeling at European level (PEF, 2013) and chosen by the Leap partnership for assessing the environmental impacts of livestock farms including large ruminants (FAO, 2016). But given that LCA requires a lot of data, and may be also time-consuming, alternative indicators have been developed and refined over time to partially assess environmental sustainability in cropping and farming systems (Bockstaller et al., 2008). MCA tools were developed to accommodate various scales of analysis, ranging from broad to specialized, and at different spatial levels. These tools can assess one or several sustainability dimensions and cater to different audiences, from research programs to direct use by farmers.



### *The DEXi tool*

Among the MCA methods, a few rely on the DEXi tool, used for multi criteria decision analysis (Bohanec, 2008). DEXi helps create hierarchical tree-shaped structures to organize and evaluate complex decision problems. At the highest level of this hierarchy are ‘branches’ representing main themes. These branches are subdivided into ‘sub branches’ for sub-themes, which in turn are broken into specific criteria. These criteria are measured by corresponding indicators, which form the ‘leaves’ of the tree. To aggregate each level to the upper one, weighting factors and utility functions are implemented on the tree.

### *DEXi-based MCA tools to assess crop systems*

For assessing cropping systems specifically, many MCA tools that are more or less complex and require more or less data were developed. Notable examples for *ex ante* assessment include MASC (Sadok et al., 2009) and its subsequent version MASC 2.0 (Craheix et al., 2012). To overcome the problem of lack of data while doing *ex ante* sustainability assessment of innovative cropping systems and take a better account of integrated pest management, the DEXi-PM tool was developed (Pelzer et al., 2012).

### *Tools specifically designed to assess dairy production systems (DPS).*

Concerning dairy production systems, different kinds of tools exist: for environmental assessment, the Annual Nutrient Cycle Assessment tool (ANCA, or Kringloopwijzer in Dutch) helps to monitor and improve nitrogen use efficiency (Holster, 2013). In France, DEXEL (‘Diagnostic Environment de l’Exploitation de l’Elevage’) is used to assist farmers in reducing GHG emissions and nutrient losses, as used in (Loyon, 2018). Simulation tools like SimSDairy, models dairy farm systems to evaluate economic, environmental and production performances (Del Prado et al., 2006). To make an *ex ante* assessment of environmental impacts (nutrient flows) based on chosen production strategies, the MELODIE model that applies to pig and dairy systems allows with a dynamic mechanistic model to calculate nutrient flows for N,P,K,Co,Zn and water across the entire farm and at a long term time scale (Rigolot et al., 2007). These tools can be very useful and quite accurate for assessing specific issues in dairy farming systems. However, they lack a holistic approach to sustainability assessment. Consequently, the evaluation may overlook impacts that could be reduced in one assessed dimension but increased in another unassessed dimension.



### *General tools to assess farm systems*

The CAP’2ER® tool, developed by the French Livestock institute, allows the assessment of environmental impacts at farm level (CAP2ER, 2022). Other tools like FarmDyn evaluate economic and environmental impacts (Britz & Kuhn, 2014). The French IDEA method (Briquel et al., 2001) is designed to assess a wide range of production systems, in the 3 dimensions of sustainability, with the latest version being the IDEA method, IDEA.4 version (Zham et al., 2023). For a comprehensive sustainability assessment, the RISE tool assessing 3 dimensions of sustainability has been globally used (Hani et al., 2003).

### *Tools at farm scale, including crops and specialized for DPS*

Specifically for dairy systems, the DairySAT (Dairy Self-Assessment Tool), which has been developed in an Australian context, aids farmers in improving practices concerning the 3 sustainability dimensions (Jennings et al., 2006). MOTIFS, has been designed to be a user friendly management guiding tool (Meul et al., 2008). Another French tool, RAD, based on the works of IDEA, SOLAGRO and the FADEAR, allows us to assess 3 dimensions of sustainability but rely on indicators that have been adapted to the west-france socio-economic context (RAD, 2010). To enhance accuracy of previously presented tools, adapt assessment to include all heterogeneous DPS across europe, and then better describe main challenges for

Table 1 :Characteristics sought in existing assessment tools to test their suitability for our objective

TOOL	DIMENSIONS	Production	Geographical context	LCA Approach
 CAP'2ER	<b>1 Environment</b>	<b>Milk</b>	<b>France</b>	<b>GHG</b>
farmDyn	<b>2 Econ &amp; Env</b>	<b>Milk</b>	<b>Norway</b>	✘
MASC2.0	<b>3</b>	<b>Crops</b>	<b>general</b>	✘
SIMSDAIRY	<b>3</b>	<b>Milk</b>	<b>UK</b>	✘
DairySAT	<b>3</b>	<b>Milk</b>	<b>Australia</b>	✘
 IDEA 4 <small>INSTITUT NATIONAL DE RECHERCHES EN EXPLOITATION AGRIKOLE</small>	<b>3</b>	<b>Farm</b>	<b>France</b>	✘
DEXiDairy	<b>3</b>	<b>Milk</b>	<b>Europe</b>	✔

Example of a few assessment tools reviewed in order to see if they could be suitable to capture interactions between dairy and crop systems in sustainability. Four characteristics were examined : the assessment of 3 dimensions of sustainability, if the tools are taking into account dairy and crop systems,if the tool is adapted at European scale, and if it includes a LCA approach. Color code : Red, not adapted; orange, uncomplete ; green, adapted for our situation.

these European DPS, the DexiDairy tool was created (Wilfart et al., 2023). The well-developed 3 pools of indicators used to assess case study farms allows to characterize trade-offs and synergies across the 3 sustainability dimensions.

*The works on a new sustainability analysis framework based on properties*

In terms of analysis framework, almost all the previous MCA methods assess one to three sustainability dimensions. Occasionally, a fourth pillar of sustainability named ‘governance’ is considered, as seen in the Sustainability Assessment of Food and Agriculture Systems (FAO, 2014). The IDEA.3 method also categorizes its indicators in sustainability properties named ‘objectives’ (Vilain et al., 2008). In this classification, an indicator can assess multiple properties. The IDEA.4 version refines this approach, categorizing 53 indicators into the classic 3 sustainability dimensions or in 5 properties of sustainable agricultural systems, with no redundancy (Zham et al., 2023). The other recent studies on sustainability properties rely on semantic approaches and word analysis (Lampridi et al., 2019; Trigo et al., 2021; Velten et al., 2015). Sustainability analysis based properties give a different perspective than the one based on 3 dimensions. Consequently, it is worthwhile to further develop these frameworks to enhance the assessment of farming systems.

*Lack of accurate assessment tools for Dairy mix farming systems:*

Many assessment tools were developed, but they are either specific to the context in which they were developed, or not specialized for mixed DPS (**Table 1**). We then would need tools that would assess DPS in the 3 sustainability pillars adapted to a European scale. Also, dairy mix farming systems present unique challenges, because interactions between crop and livestock occur, like forage used to feed the herd or manure used to fertilize crops. Moreover, technical crop management practices may differ in mixed farms compared to specialized farms. To accurately highlight the environmental, social and economic impacts of these mixed dairy systems, it is not sufficient to merely combine the impacts of cropping and DPS separately. Otherwise we would fail to capture the synergies and trade-offs between crops and DPS. While there are accurate MCA assessment tools available for cropping systems on one side, dairy systems on the other side, an accurate Dairy mix farming sustainability assessment systems, that would include LCA indicators is still lacking.

Regarding the available methodology and issues on milk production systems, we can wonder **how to improve the multi criteria sustainability assessment of dairy mix farm systems?**

### 1.3 DairyMix, the European project frame of the internship

DairyMix project is an European research project in multicriteria assessment, decision support and management tools development for sustainable circular mixed farming systems in dairy production. DairyMix began in 2022 and will last mid2025. The goal is to produce a tool to guide the changes toward more sustainability for mixed DPS, with a special focus on the reduction of GHG emissions. To do so, the main action is to increase their circularity at least towards nitrogen fluxes (reduce the inputs such as concentrates and mineral fertilizers). This project uses multi criteria assessment and develops modeling, decision and management tools adapted to dairy mixed farming systems. The project also includes a case study approach, with the assessment of 28 farms from 7 different countries: Ireland, France, Italy, Germany, Poland, Norway and Argentina. This project is following the Milkey project (<https://www.milkey-project.eu/>). The aim is to extend Milkey’s tool that already assess sustainability of specialized dairy systems to a tool that is able to assess sustainability of mix farming systems (dairy systems with crop productions in the farm). The results will be used to build a web platform Milkey/DairyMix to provide context specific management strategies

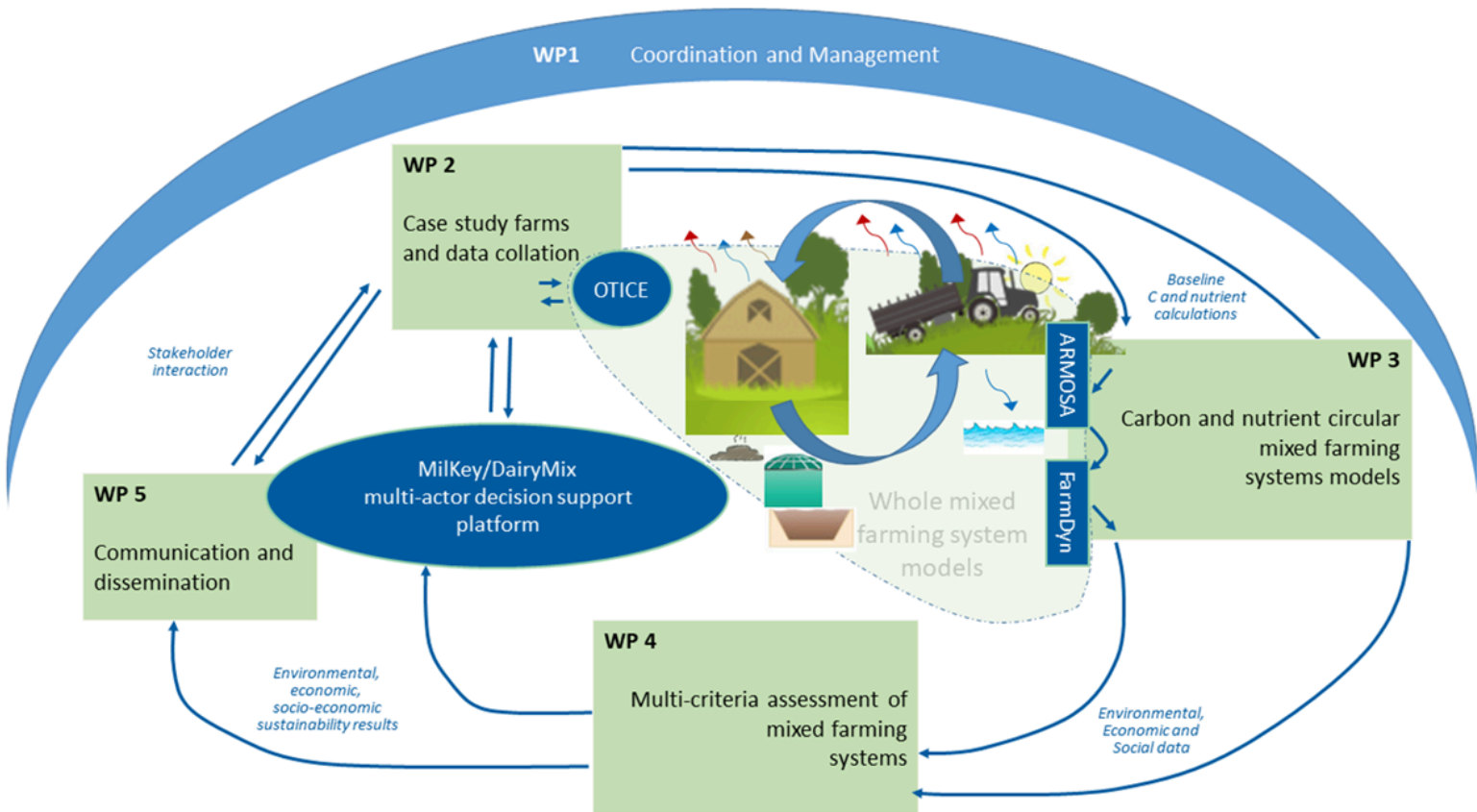


Figure 4 : Organisation of the different work packages in the DairyMix project.

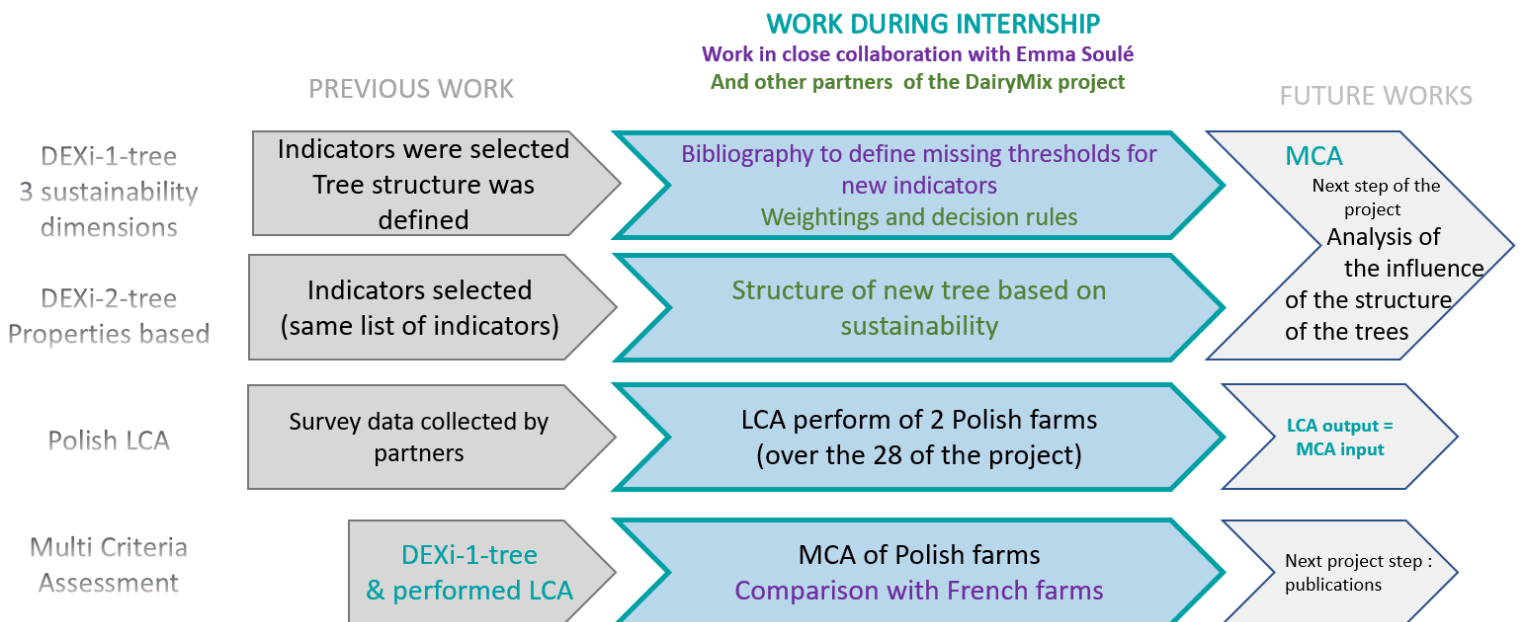


Figure 5 Illustration of the missions presented in this report and their integration in the DairyMix project

for key European regions and Latin America. In the DairyMix project, 10 partners institut worked in collaboration: ATB (Leibniz institute for agricultural engineering and bioeconomy), ILVO (Flanders research institute for agriculture, fisheries and food), INRAE (French national research institute for agriculture, food and environment), INTA (Argentinian national institute of agricultural technology), NIBIO (Norwegian institute of bioeconomy research), RURALIS (Norwegian institute for rural and regional research), TEAGASC (Irish agriculture and food development authority), UCD (school of agriculture and food science of University College Dublin), UMIL (University of Milan) and UZ (Polish University of Zielona Góra).

DairyMix project is organized into five Work Packages (WP)(**Figure 4**). The WP4, related to the multi-criteria assessment of mixed farming systems for dairy production, is managed by INRAE, for the expertise they have in this subject. The WP4 is divided into 5 tasks. Each task - environmental, economic and social assessment - will be led by a specialist partner (INRAE, TEAGASC, and University of Zielona Gora). The final multi-criteria assessment will be also coordinated by INRAE as well as the analysis of trade-offs and synergies between the sustainability pillars. INRAE is responsible to design, define criteria, select indicators (and associated thresholds) for the environmental branch of the DEXi tree and is also responsible to make the global aggregation rules for the whole tree (with the criteria and indicators selected by partners for the Economic and Social indicators).

During my internship, I worked on tasks included in the WP4 of the project. I worked on mixed DPS sustainability from a conceptual approach and applied it to Polish farms case studies (**Figure 5**). I worked on 3 interconnected tasks: finalization of the first DEXi tree tool, the building of the second DEXi tree that explores a new analysis framework and the case study assessment of 3 Polish farms.

- The first step, a conceptual approach, was to support the finalization of a new DEXi tree tool that aims to assess specifically the mixed DPS. The general structure and all the indicators were already defined. Support from my side was needed to establish the threshold of the new environmental indicators (new compared to the Milkey project), and establish the weighting and aggregation of branches. This part is conducted through a collective work with the other members of the project. The main deliverables of this task will be a Dexi tree and a handbook that gather and explain all the indicators of the DEXi tree. **This report will present the final DEXi-1-tree, as well as the methodology used for weightings and thresholds steps , and the definition of all the indicators.**
- The second step is also a conceptual approach, we build the framework of a second DEXi tree with the same indicators but with a different structure. In this tree, indicators are grouped by sustainability properties in order to explore a new frame of analysis. **This report will present the new frame of analysis and the structure of the DEXi-2-tree.**
- And the last step of my internship is the assessment of 2 Polish case study farms of the project, through a LCA and the DEXi-1-tree Multi Criteria Assessment. **Results of LCA, environmental and social MCA assessment with the DEXi-1 tree analysis will be presented and compared to French farms results.**



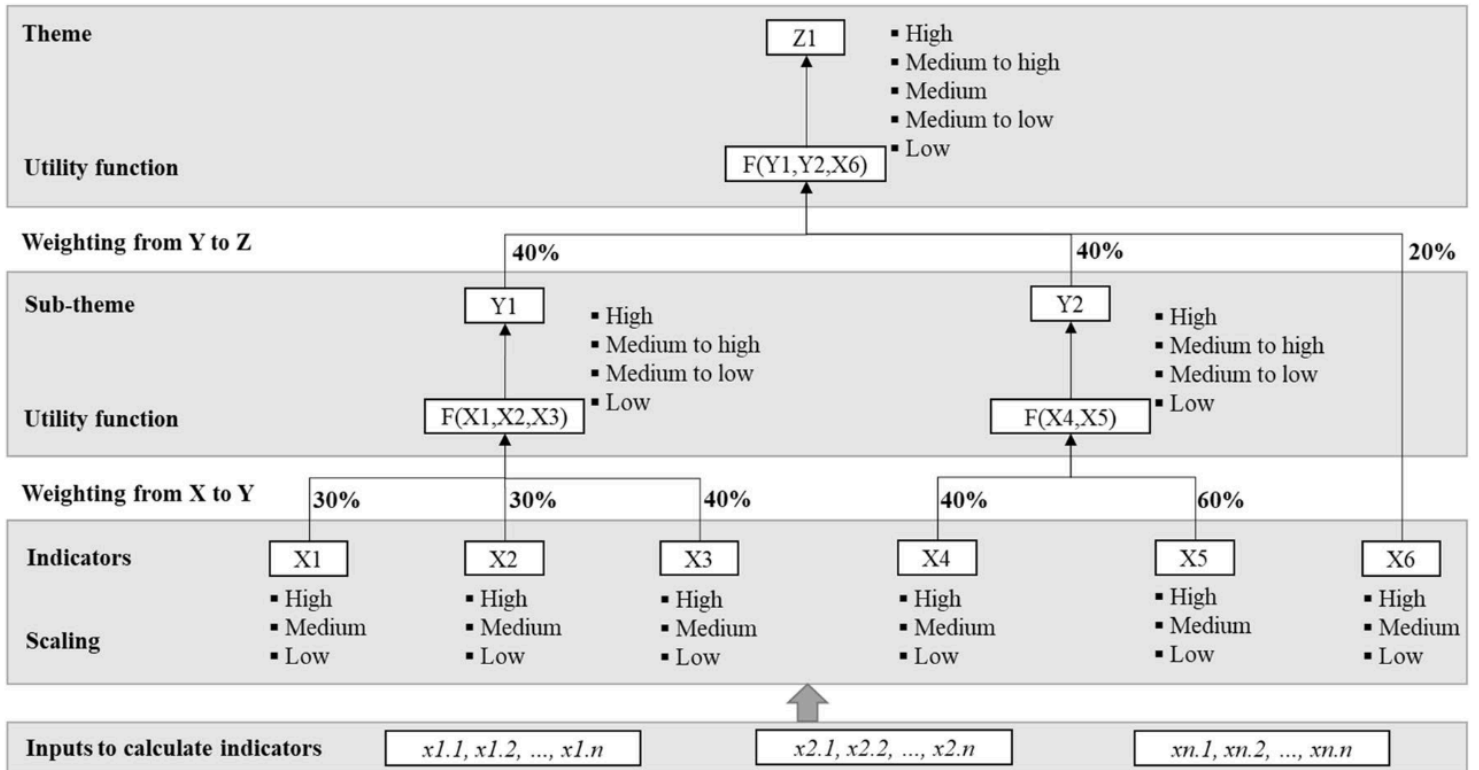


Figure 6 : Organization of the hierarchical multi attribute DEXi model with a theoretical example. The lower line represents the data input ( $x_1 \dots_n$ ) used to calculate indicators ( $X_1 \dots_n$ ). Each sub theme ( $Y_{1 \dots n}$ ) and theme ( $Z_1 \dots_n$ ) is assessed by their respective utility functions  $F(X_n)$  or  $F(Y_n)$  using corresponding weightings (Wilfart *et al.*, 2023).

## 2 MATERIAL AND METHODS

### 2.1 Methods for Multi Criteria Assessment

The assessment relied on indicators from the three dimensions of sustainability : environmental impact from cradle to farm gate, social impacts and associated economical returns. To perform MCA, the DEXi tool 5.05 version (Bohanec, 2021) was used to aggregate indicators. A first tree, **DEXi-1-tree**, which branches group indicators by the 3 sustainability dimensions, was finalized. A second tree was built, **DEXi-2-tree** using the same indicators but re-organizes them in 5 branches, aggregating criteria that represents properties linked to sustainability. This MCA method was designed to assess 28 farms from 7 different countries: Ireland, France, Italy, Germany, Poland, Norway and Argentina.

#### 2.1.1 DEX method

DEXi is a software specialized in multi-attribute decision-making. Its goal is to facilitate the design of qualitative multi-attribute decision models by supporting interactive and participative development (Wilfart et al., 2023)). The software displays and assesses the different selected systems by breaking down a decision problem into several sub-problems, which are easier to solve than the primary one (Bohanec, 2021). It associates a hierarchical decision model with an expert perspective, based on discrete qualitative attributes expressed with statements such as “low”, “medium”, ” high”, rather than numbers (Craheix et al., 2015). Attributes are organized in a tree shape structure, establishing dependencies with attributes from the lower and upper level **Figure 6**.

In our sustainability assessment, each dimension (environmental, economic, or social) is divided into themes (third level), further divided into sub-themes (intermediate level), which are themselves assessed by indicators (lowest level). Indicators are directly assessed by users through models or direct measures (Lairez et al., 2016). Then, each assessed dimension results is obtained from aggregation of lower themes results, which are themselves determined by sub-themes, determined by corresponding indicators assessed individually.

Craheix et al. (2015) proposed a five-step methodology for building a DEXi model, refined by Le Feon et al. (2021) and recently adapted by Wilfart et al (2023) to design a tree to assess specialized dairy farms (DEXiDairy):

1. **Analysis and design plan:** This crucial step in the development of the MCA model consists in defining the assessment boundaries, objectives, actors, and research institutes that will be involved (Bohanec 2020).
2. **Building the hierarchical tree:** The tree is built by a panel of experts based on the assessment’s objectives and context defined at the first step. Two approaches can be used, top-down or bottom-up. In the top-down approach, the design starts from the root of the tree ("dimension" level) and proceeds to the leaves ( "indicator" level). The bottom-up approach starts with the selection and design of indicators, which are then aggregated to the superior levels in sub-themes, themes, and finally dimensions). This step is participative work, involving strong interaction among different stakeholders.



Figure 7 Social and Economical branches of the DEXi-1-tree

\* As Viability and Resilience are now also properties of the DEXi-2-tree, these names will be changed in order to avoid confusion

3. **Selecting and designing indicators:** For each sub-theme, the quantitative indicators (based on data collection, calculation, or model estimations) are transformed into qualitative ones. This is done through a scale of reference values defining the correspondence between quantitative value obtained from the indicator and the corresponding qualitative class like “high, medium, low”. Therefore, in the DEX methodology, this step is called "scaling", and is usually done using threshold values from the academic and gray literature (Bohanec 2020). Since the number of classes and the values of the threshold sets determine qualitative value taken by indicators, this step is always a compromise between result accuracy and model simplicity (Craheix et al. 2015). It is not recommended to associate too many indicators with too many qualitative scales. For each indicator, the number of classes on the scales can go up to seven, but it is advised to keep this number as low as possible, then increase the number of classes at the superior levels (Bohanec 2020).
  
4. **Parametrization :** This key step involves establishing decision rules between lower levels (X or Y in our example) and their corresponding upper levels (respectively Y or Z) **Figure 6**. The attributes are aggregated to the next attribute level by a utility function and a weighting procedure. Concretely, a weight is assigned to each attribute and a utility function is defined. This function takes the form of a lookup table using "IF-THEN" decision rules. *For example, IF indicator X1 is "high" AND indicator X2 is "low," THEN sub-theme Y1 is "medium."* The maximum number of indicators to aggregate in the DEXi software is four, but it is advised not to combine more than three (Bohanec 2020).
  
5. **Evaluation and interpretation of the results:** The final step consists of evaluating and interpreting the obtained results.

The development of DEXi-DairyMIX-trees that followed these steps is detailed in the following sections.

### 2.1.2 Finalisation of DEXi-DairyMIX-1-tree based on 3 sustainability dimensions

#### *Structure, indicators*

The DEXi-DairyMIX-1-tree is an adapted version of the tree designed for specialized dairy farms during the Milkey project (Wilfart et al, 2023). Social branch has been refunded and expanded, from 6 criteria assessing the equilibrium between professional and personal life, to 19 assessing safety, security, well-being, self-actualization and ability & will to progress **Figure7**. This development was necessary in order to better capture and accurately characterize the social impacts of mixed dairy farms. Economic criteria has been increased from 12 to 20 in order to better characterize the economic model of the mixed farm, the different salaried status of people working on the farm and the integration of the farm's economical model in the country's economy **Figure 7**. The environmental branch had been upgraded, modifying some indicators and adding others to capture impacts of crop production which was absent from the DEXiDairy tree **Figure 8**. In particular, new indicators have been added mainly to develop biodiversity conservation sub-branch. As a result of the modification of the tree and in particular its expansion, it was necessary to find threshold values for the new indicators and to adapt those of certain indicators in order to be able to discriminate mixed dairy farms.

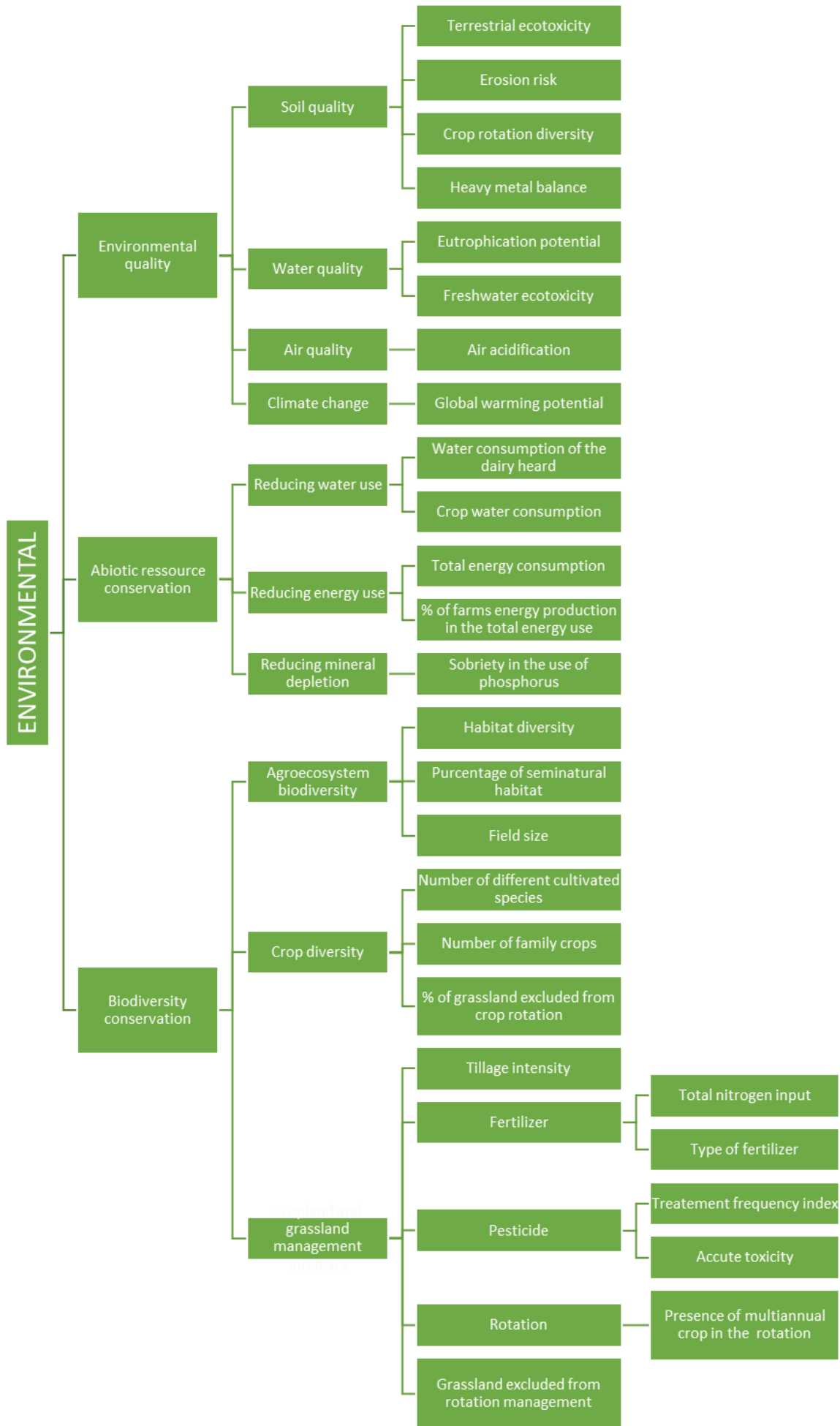


Figure 8 : Environmental branch of the DEXi-1-tree

### *Threshold establishments*

In the context of the DairyMIX project, it is important to underline that the DEXi-DairyMIX-1-tree aims to assess sustainability of mixed dairy production systems from different European countries. Thus, thresholds were set to fit for this context and are not country specific. They have been defined in order to distinguish among the different levels of integration of mixed crop and livestock production systems. As underlined by Le Féon et al. (2021) and Wilfart et al (2023), comparing production systems at European level requires the use of common scales even if sustainability performance, in particular in the economic and social branches, can differ across regions. Thus, we made the choice to develop common and non-country specific scales to compare performance among the case study farms of the project.

Concerning the thresholds setting for the new 14 environmental indicators, it was based on literature review and performed as a co-work with Emma Soulé. The methodology was first to define key words for cross reference research on the WOS and SCOPUS tools. The aim of this query was to capture all the studies using at least one of the environmental indicators chosen for the DEXi tree in agricultural production systems. Then adequacy of the published thresholds to our boundaries and objectives was checked. If not, a meta analysis was performed to define the value range or to select studies the closest to the perimeter of the project to select reference values and then establish thresholds based on expert decision. **Appendix 1** gives the list of new indicators with their definition. New established thresholds for the assessment work are given in **Appendix 2**. Thresholds for indicators that are common with the Milkey project are the ones from the handbook (Baillet et al., 2022).

Thresholds for economic and social indicators will be set by their respective task leaders, namely Teagasc (Ireland) and University of Zielona Gora (Poland). Briefly, for most of the economic indicators, reference values will be based on the distribution of data of dairy farms from the EU FADN public database. If the necessary data to scale indicators are not available in the EU FADN database, reference values will be defined using the data collected on the 28 case study farms. As all calculations are not performed yet, we will not use the economical indicators for these firsts case study MCA assessment.

Concerning the social indicators, a balanced 3 classes assessment was chosen, to range quantitative values obtained from the Likert scale.

At the end of the indicator calculation phase for all the project's case studies, the ability of the selected threshold values to discriminate between farms will be assessed by feeding the DEXi-Dairy model with data from the case studies. A final adjustment of the threshold values will then be made in order to better differentiate the farms on the basis of their sustainability performance.

### *Weighting process*

In order to have a tree that assesses in a relevant way local contexts in different countries, and considering that the thresholds are the same for all the countries, we defined different weightings. As the partners of the DairyMix project decided that Environmental, Social and Economic branches are equally important, they have the same weight (33.3%). Inside each branch, all criteria, sub-criteria and indicators have a country specific weight. The weighting process involved all partners of the project. The INRAE team organized 2 On-Line workshops: one to present the weighting process of criteria and indicators of the environmental branch and another one for the social and economic branches. Before the workshop, synthetic documents were sent to the attendees in order to recall the weighting



process and the definition and meaning of the indicators. During these workshops, which brought together as many partners as possible, the participants were invited to individually weigh tree nodes against each other at each hierarchical level. Weights had to add up to 100% at each level using the Wooclap interactive tool. The weights have to be adapted to their own country. Partners that could not attend the workshop had the opportunity to express their opinion, filling afterwards the online Wooclap questionnaire. Then results per country were sent back and partners had a few weeks to discuss internally to find an agreement on weighting values for their own country. Final weighting had to reflect a consensus between partners of the same country. They were also invited to specify the reasons for their final choices. For Poland and France, respectively 4 and 5 people participated in the decision process.

#### *Aggregation rules set in the utility function*

For each aggregation node, the utility functions were calculated by the DEXi software using a multiple linear regression formula ( $y = a x + b$ ), where the weights of each indicator from the previous level (X1, X2, X3 or Y1, Y2) and the number of classes of the following level (Y1 or Z1) were used to calculate a and b (**Figure 6**). Then, the DEXi software rounded up the value of y by adjusting the weights of each indicator from the previous level (X1, ...). We used these adjusted weights proposed by the model to generate all the utility functions of the DEXi-DairyMIX-1-tree.

### **2.1.3 DEXi-DairyMIX-2-tree based on sustainability properties**

The objective of the second tree was to reuse all the indicators without adding others and to organize them according to sustainability properties. To build this second tree, monthly workshops with partners have been organized. To organize the indicators into sustainability properties, we applied 2 different methods. The first one was a bottom up approach, by finding similarities between indicators in order to group them by properties. The main problem was to extract the indicators from the 3-dimensional framework to which we are accustomed and to reclassify all the indicators. Then a top down approach was applied, we iteratively refined the sustainability properties taking inspiration in the literature for the sustainability concepts found in the bibliography that could include all our indicators. Then we arranged the indicators to avoid redundancy. During the other meetings, we then moved some indicators, in order to put them in the most relevant property. Indeed, we cannot have redundancy in this second tree, and as indicators have been selected before the establishment of the second framework, we made a choice for some indicators between several properties. We then refined the structure of the tree to organize the branches.

## **2.2 Case study farms and data collection**

Criteria for farm selections were the following: farms with dairy production system and culture, with several levels of circularity in nitrogen. Therefore, they have not been selected to be representative of the farming system of the country (for instance, mix farms are not common in Ireland). This report presents the assessment for 3 of the 6 Polish farms. A comparison with French farms was also made in order to compare different practices and levels of crop integration in DPS. Data were collected from a survey conducted by Polish partners for the year 2021, from January to December. Some multi-annual information like crop rotations may go back to 2018. Similar templates were filled for all the farms of the



Table 2 : Main characteristics of Polish farms

<b>FARM</b>	<b>Center Poland PULS04</b>	<b>North Poland UZ01</b>
Grazing	NO	YES
Dairy Cows	12	66
Raw milk kg FPCM / year	89 866	238 471
UAA ha	60	40
Grassland excluded rotation in ha	10	15
Crops in rotation ha	50	25
Main crops	Maize Wheat Triticale Rapeseed	Wheat Maize silage & grain spring barley
Minority crops		Potato Phacelia Rapeseed Grassland with alfalfa

project. All data were not shared publicly because of some confidential information, farms will be identified with a corresponding code to respect the GRPD rules. Farm data comes from the data collection team (WP2), main characteristics are shown in **Table 2**.

#### *Data estimate*

For the farms giving purchased concentrates (mixed ingredients like soybean meals, oils, vitamins, minerals, amino-acids, ...) in the ration, we missed some data because for confidential reasons, ingredients percentage are not always indicated by the feed manufacturer. Data gatherers indicated the available list of ingredients and total amount of proteins and fat of the final concentrate product. To estimate ingredient proportions, we used the feed ration formulator NASEM Dairy-8 tool developed by the University of Davis (California, US). The advantage of using a formulation software is that we could also implement other information like the daily milk production of the cows with its fat and protein content, bred of the herd, ... With this method, compared to ingredients formulation alone, we give more information to the software to solve the formulation problem and then approximate as well as possible the real concentrate composition. .

### 2.3 Calculation of indicator from LCA assessment

#### 2.3.1 Definition of the assessed system and objectives

*Global objective of the LCA:* to quantify the environmental impacts of the farm

*Functional Unit :* production of 1kg of **Fat and Protein Corrected Milk (FPCM)**. We do refer to the following equation from (International Dairy Federation, 2015) :

$$FPCM = Total\ milk\ produced * Milk\ density * (0.1226 * Fat\% + 0.0776 * Protein\% + 0.2534)$$

*Total milk produced* = Total milk produced in L

*Milk density* = 1.032 kg/L

*Fat%* = Fat content of the milk produced in %

*Protein%* = Protein content of the milk produced in %

*Processus and system boundaries:* LCA is performed from cradle to farm gate (as it has been decided in the DairyMix project guideline, to ensure the coherence of the analysis with the rest of the project's milestones).

*Concerning the allocations* of impacts among product and coproduct, the allocation rule was set as economic allocation following the allocation rules recommended by the PEF guideline (European Commission, 2018) and Agribalyse (Colomb et al., 2015). except for some categories of products (grain / straw : mass allocation; Cow, culled cows and newborn : biophysic allocation)

#### 2.3.2 Establishment of the life cycle inventory using MEANS InOut platform

All fluxes of material and energy that cross the system are quantified as well as the emissions to the air, water and soil to establish the life cycle inventory. This step is performed with MEANS-InOut 4.4.1 software. This software relies on Agribalyse® guidelines (Colomb et al., 2015). The background data that support this inventory come from Agribalyse 3.1.1 and ecoinvent 3.9 as implemented in Simapro 9.5 Software.



### 2.3.3 Impact analysis with Simapro ®

To aggregate the inventory into potential environmental impacts, the EF 3.1 characterization method was chosen as recommended in the PEF and Agribalyse ® guidelines. In order to have all the indicators we selected for our project, we also used the ReciPe method.

### 2.4 Calculation of indicators that do not depend on LCA

Social indicators were assessed by Joanna Fratzak-Muller from the university of Zielona Gora in Poland. To assess the indicators, farmers and/or family members had to answer a survey with statements that they had to note with several options, following the Likert scale from 'I totally agree' to 'I totally disagree'.

Calculations of economic indicators will be performed by the Teagasc institute of Ireland. The methodology they selected to set the thresholds for economical values (quartile method) requires them to calculate all the farms of the project to obtain these values. Thus, for the MCA results presented here on Polish farms, we will make a focus on environmental and social indicators.

Table 3 : Weightings of environmental branch for Poland and France

Institute Country (experts in decision process)	UZ Poland (4 experts)	INRAE France (5 experts)
	weighting in %	weighting in %
Terrestrial ecotoxicity	15	10
Erosion risk	40	40
Crop rotation diversity	35	40
Heavy metal balance	10	10
Eutrophication potential	60	60
Freshwater ecotoxicity	40	40
<b>Soil quality</b>	<b>25</b>	<b>25</b>
<b>Water quality</b>	<b>20</b>	<b>20</b>
<b>Air quality</b>	<b>20</b>	<b>20</b>
<b>Climate change</b>	<b>35</b>	<b>35</b>
Water consumption of the dairy herd	60	40
Crop water consumption	40	60
Total energy consumption	50	65
% of farms energy production in total energy use	50	35
<b>Reducing water use</b>	<b>35</b>	<b>40</b>
<b>Reducing energy use</b>	<b>35</b>	<b>40</b>
<b>Reducing mineral depletion</b>	<b>30</b>	<b>20</b>
Habitat diversity	40	40
Percentage of semi-natural habitats	40	35
Field size	20	25
Number of different cultivated species	25	25
Number of family crops	25	30
% of grassland excluded from the rotation	50	45
Total nitrogen input	50	54
Type of fertilizer	50	46
Treatment frequency index	40	40
Acute toxicity	60	60
Tillage intensity	15	15
Fertilizer	35	25
Pesticide	25	30
Rotation	25	30
<b>Agroecosystem biodiversity</b>	<b>30</b>	<b>30</b>
<b>Crop diversity</b>	<b>20</b>	<b>20</b>
<b>Cropland and grassland management</b>	<b>30</b>	<b>20</b>
<b>Grassland excluded from the rotation management</b>	<b>20</b>	<b>30</b>
ENVIRONMENTAL QUALITY	40	40
ABIOTIC RESOURCES CONSERVATION	20	30
BIODIVERSITY CONSERVATION	40	30

Indicators are in normal typography, sub branches are in **bold typography** and main branches of the environment branch are in capital letters. Colored cells correspond to indicators/sub-branches/branches which were given more weight for the corresponding country compared to the other one. Light blue corresponds to a difference of 5 points, middle blue to a difference of 10 points and darker blue to a difference of 20 points.

## 3 RESULTS

### 3.1 First DEXi tree

The method previously described was used to build the DEXi-DairyMIX 1 tree, which is divided into three main branches related to the three sustainability dimensions. In order to describe the complexity and characteristics of mixed DPS, the model gathered 25 environmental indicators, 20 economic indicators and 19 social indicators.

#### *Weightings*

The first tree considered each sustainability dimension equally (weighting factors of 33.3% each) in order to capture the whole concept of sustainability.

Weightings for France and Poland for the environmental branch are gathered in **Table 3**.

For the environmental branch, weightings decided by both French and Polish groups were quite similar. The meeting to harmonize weights among partners had not yet taken place at the time of writing this report. Thus, we only have the explanations for the French ones. At the indicator stage, the biggest difference between French and Polish weight can be found in the reducing water use sub-branch. In France, we decided to attribute a 60% of weight for *crop water consumption* and 40% for *water consumption of the dairy herd*. We did consider that crop irrigation is the main issue concerning water use in a context of climate change. Furthermore, we have more technical levers to reduce crop water consumption than what we have for the dairy herd [1], which include drinking water of the cows and water used for washing. Polish partners did a reverse choice, with more weight for *water consumption of the dairy herd*. Another small difference is between *total energy consumption* and *percentage of farm energy production in the total energy use*. Polish partners assigned the same weights (50%). In France, we chose to highlight *total energy consumption* because we considered that in order to be sustainable, we have to first reduce the total energy consumption, and then produce the energy with the lowest impact possible. Other small differences can be observed in the weight between indicators but the difference is minimal.

At the main branches stage, the biggest difference that could impact in further analysis was the difference in the weight between *Abiotic resources conservation* branch and *Biodiversity conservation*. Indeed, the French team decided to highlight the *Abiotic resources conservation* branch with a percentage of 30 % (vs. 20 %) while the Polish Partners insisted more on *Biodiversity conservation* (40 %) vs. a weight of 30 % decided by the French group.

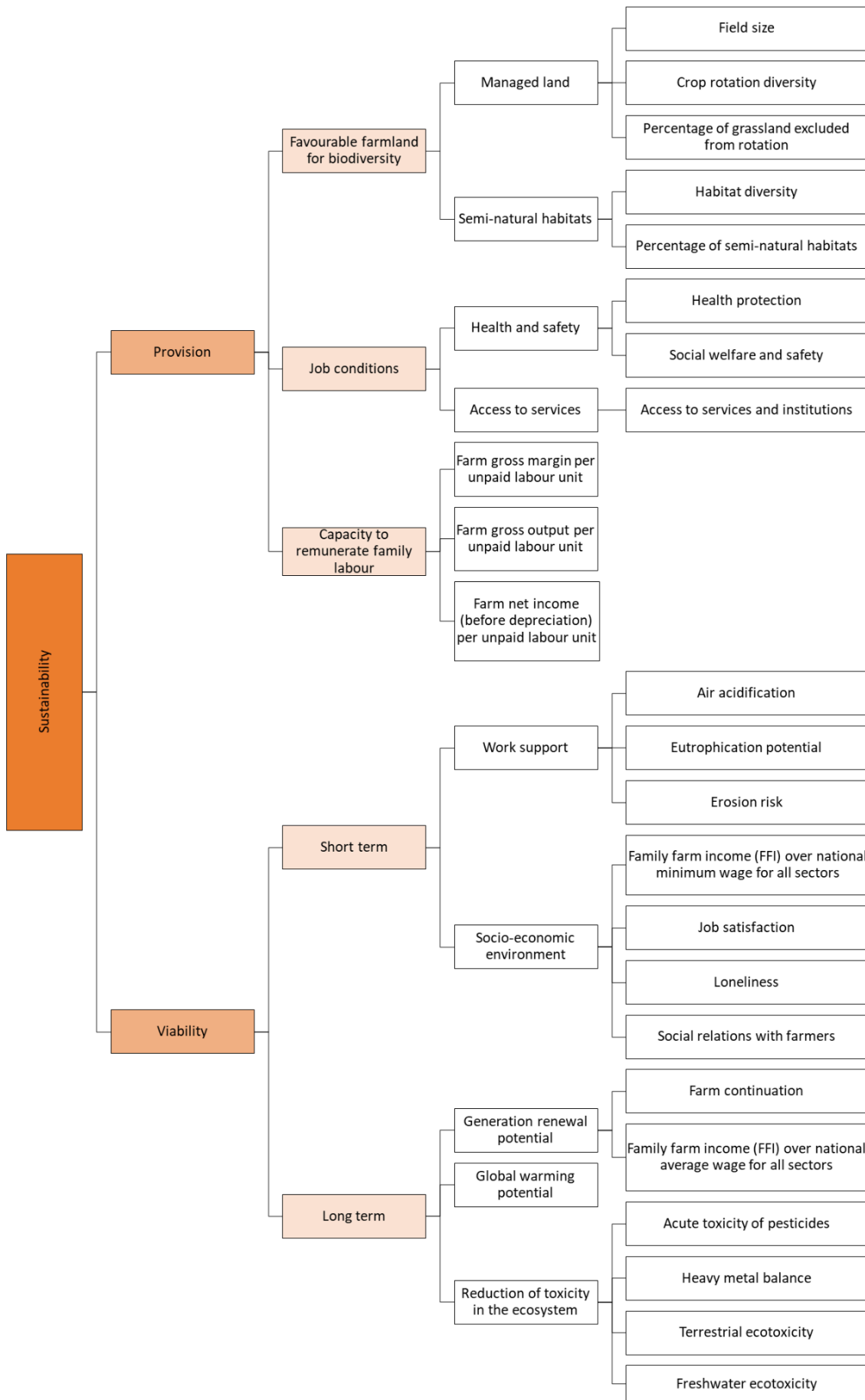


Figure 9 : DEXi-2-tree provision and viability branches

## 3.2 Second DEXi tree new conceptual assessment framework

Grouping sustainable indicators by properties in a new framework was a work that will give different highlights depending on the selected indicators and of course the chosen definition of sustainability. The definition of sustainable system that drove our work is the one by Lewandowski *et al* (1999), namely, “management and utilization of the agricultural ecosystem in a way that maintains its biological diversity, productivity, regeneration capacity, vitality, and ability to function, so that it can fulfill – today and in the future – significant ecological, economic and social functions at the local, national and global levels and does not harm other ecosystems” The Second DEXi tree was based on 5 properties. Of course, these properties did not pretend to be exhaustive or absolute. Two over the five properties could not be considered inherent to sustainable systems: *Provision* and *Viability*. The three other properties had been chosen because they seemed relevant to assess sustainability in our current context: *Efficiency & Sobriety*, *Resilience* and *Autonomy*. Hereafter are detailed the 5 selected properties and the reasons for this choice.

### *Provision*

Based on this definition of sustainability, we first selected the property Provision, which aimed to assess the ability of the system to provide services, and that we understood as ‘meets the needs of the present’. Our Provision concept here corresponded to a wide scale definition of productivity that include :

- the production from an economic point of view,
- the system provided structural elements that will be a support for biodiversity and helps to develop ecosystem services
- the production system provided a qualitative working environment for the farmer

This branch was then divided into 2 sub-branches (**Figure 9**) : *Favorable farmland for biodiversity* with environmental indicators - which were split in 2 sub branches *Arable land* and *Semi natural habitat* - and *Farmer job conditions* with social and economical indicators.

### *Viability*

The second selected property was Viability. We defined it as the ability of the system to remain in time, to preserve the ‘long term’ production conditions in an environment where we don’t consider perturbations. This property aimed to assess:

- the economical viability, assessed by the economical balance of the farm
- the good conditions for the farm ecosystem to produce, here mainly assessed by the absence of environmental pollution (that may compromise health of farmers or ecosystems)
- the viability of working conditions

This branch was divided into 2 sub-branches (**Figure 9**) : *Short term* for the elements that relied on mechanisms that could happen on average in one year or on one cultural season and *Long term* for mechanisms that had more inertia. The Short term sub branch was itself divided between *Degradation of production support* which group environmental indicators and *Social environment* which was characterized with social and one economic indicator. In the Long term sub branch, 4 environmental indicators were grouped in a sub branch *reduction of toxicity in the ecosystem*.



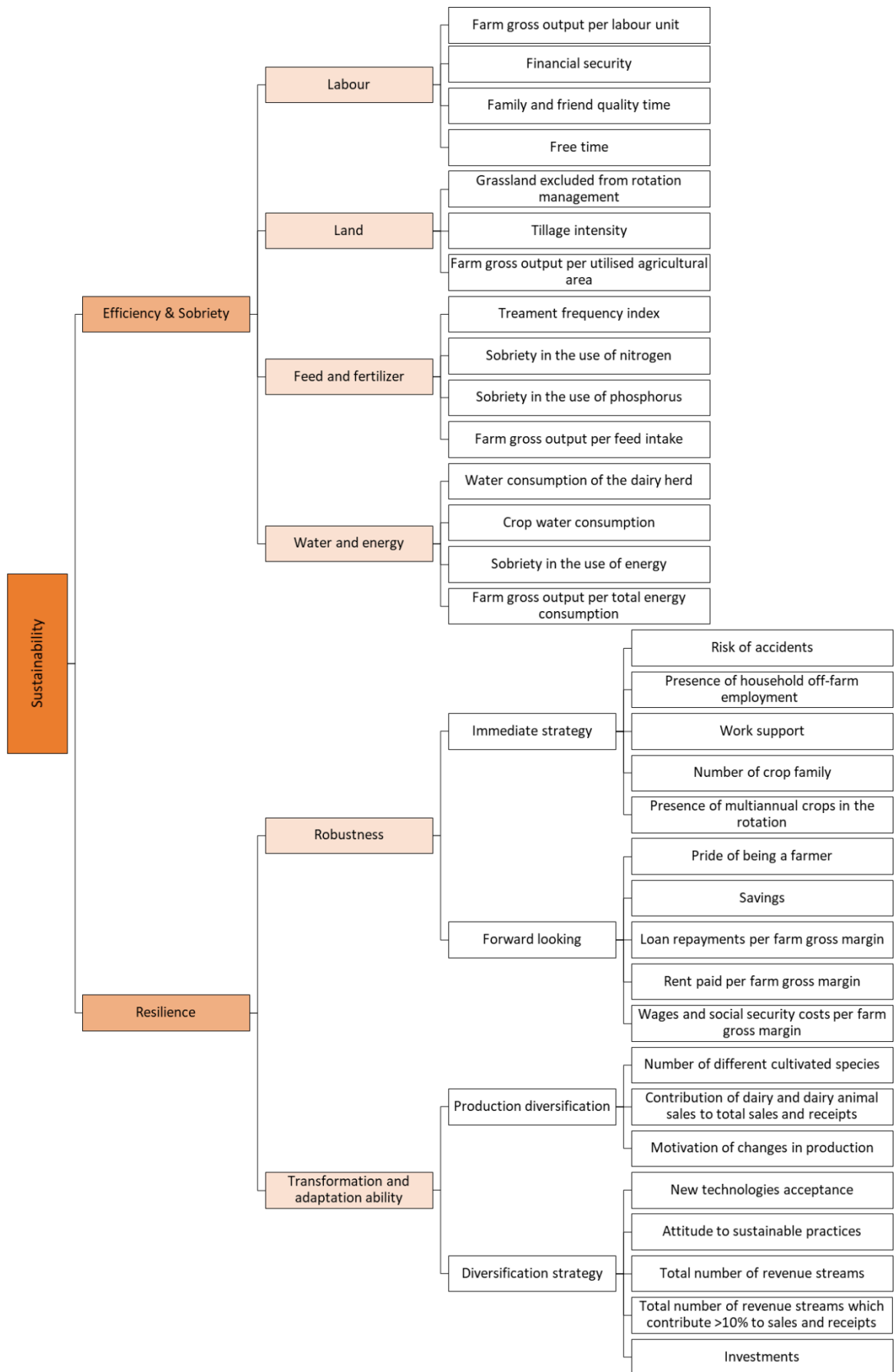


Figure 10 : DEXi-2-tree Efficiency & sobriety and Resilience branches

## *Efficiency & Sobriety*

The third property grouped the two concepts. The first one, *Efficiency*, was the ratio between production over the inputs. The second concept, *Sobriety*, was the ability of the system to produce with few resources.

Efficiency and sobriety may not be considered as inherent properties of sustainability, because it assessed systems that already had perfect provision level and were perfectly viable, they could be considered sustainable. But here in our context, human societies faced resource scarcity and had to share limited resources. Then, we considered that efficiency and sobriety were increasing sustainability of the systems in the way that they prevented tensions on the share for resources.

In this branch, we used indicators to assess:

- economical efficiency,
- ‘social sobriety’ in human resources
- sobriety in the use of environmental resources

This branch was divided into 4 sub-branches (**Figure 10**) that corresponded to types of resources that may be in tension : *Labour, Land, Feed & fertilizers* and *Water & energy*.

## *Resilience*

Fourth property was named *Resilience*. Many definitions of resilience could exist depending on the study field (Quinlan et al., 2016). The definition we chose was based on the work of Darnhofer, (2014) who defined properties for resilient farms. His resilience property corresponded to the ability to face perturbations, either to resist shocks and come back to normal situations or to modify its functioning to come back to normal situations in adaptation or transformation process. This definition relied on the 3 properties of resilient farm that we explained here and brightened with examples:

- The first was buffer ability or also called robustness, which was the ability to resist shocks and come back to normal situations without any change in its way of functioning. *For example, if a farmer faced a drought one year and harvested less grass than usual, will he still have enough grass to feed his cows or will he need to buy some grass?*
- The second was the adaptation properties, which traduced the ability of a system to make few modifications, and adjusted in order to face perturbations. *For example if we face multiple droughts, can we diversify our land units to share the climatic risks and have a more stable production?*
- The third one was the transformation ability, which corresponded to the ability to operate drastic changes in production systems. *For example: facing climate changes, can we change the breed of the herd? Another example with an economic perturbation : facing a drastic fall in milk prices, an intensive dairy farm may evolve towards a more sparing or self-sufficient system, which may involve setting up a new production workshop, a new marketing method, etc.*

Here, we included the resilience concept inside the sustainability one. As any farming system was susceptible to face perturbations, ability to resist shocks or to transform were more likely to persist in time.

This property aimed to assess how the production system could face perturbations, and we divided it into 2 sub branches (**Figure 11**): one to group the indicators assessing the *Robustness* and another to group indicators relating to the ability of the system to modify its functioning *Adaptation & Transformation ability*. This transformation & adaptation ability

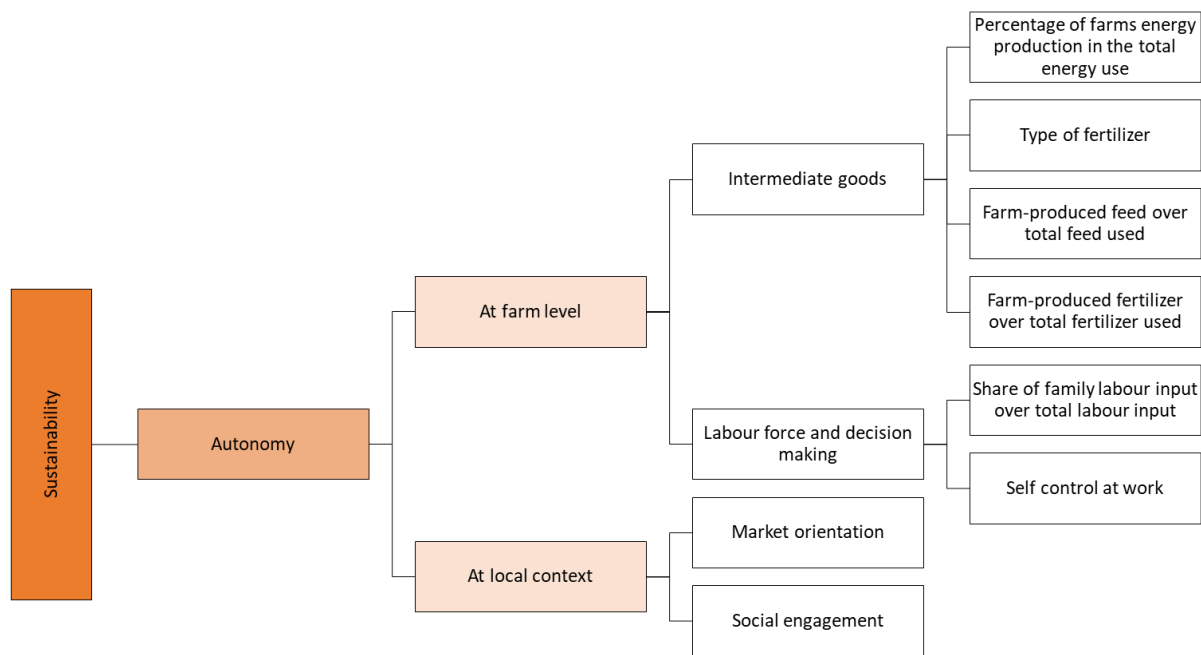


Figure 11 : DEXi-2-tree Autonomy branch

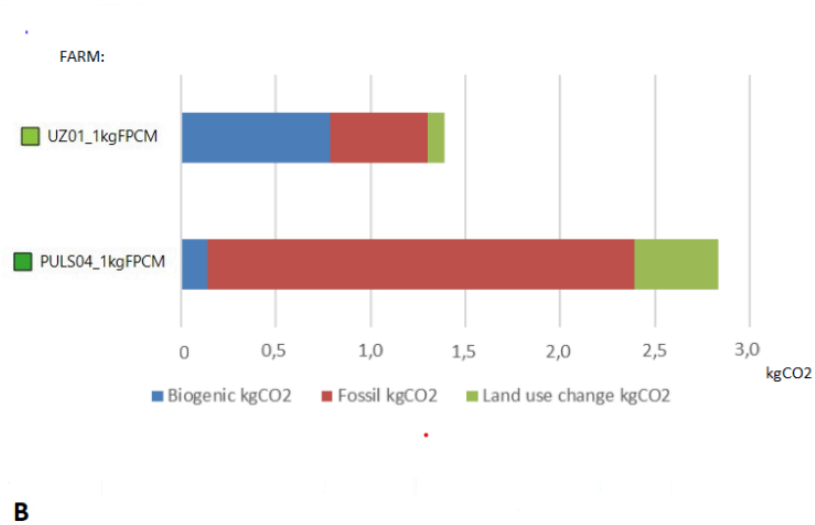
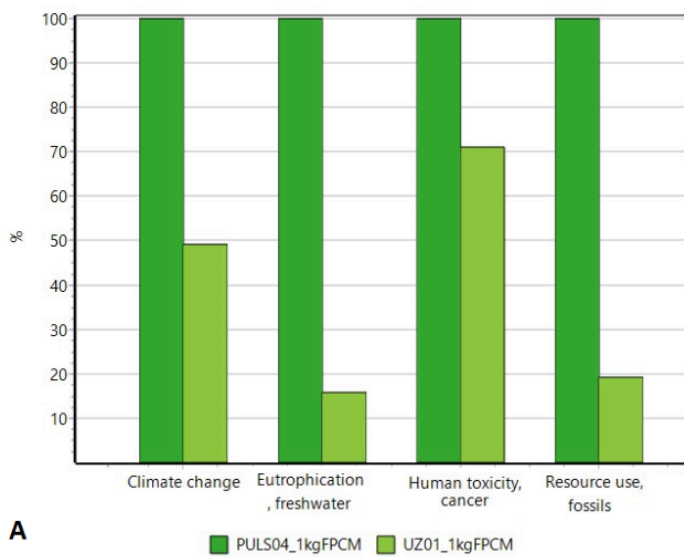


Figure 12 Impact categories of LCA analysis

A Environmental impacts of UZ01 farm in % of the PULS04 farm

B Detail of Climate change impact : proportions of CO2 equivalent by category : biogenic, fossil or land use change.

sub branch was itself divided into 2 sub branches: *Production diversification* and *Diversification strategy*.

#### *Autonomy*

Fifth property was named *Autonomy*. The concept we put behind was a large-scale definition of autonomy and, not a strict self sufficiency. We defined it as the ability of the farm to be self-sufficient for its main production factors and to contribute to the sustainability of the territory to which it belonged. We here assessed sustainability at farm level but some functions, depending on the needs, were more relevant to be assessed at territory scale. *For example: the availability of veterinary services is more relevant at territory scale. Another example is the autonomy in fertilizer that can be assessed at farm scale or with direct neighborhood.*

Autonomy was not an intrinsic sustainability property. Having a high autonomy level prevented consequences from outside perturbations. Then, this property could help to assess sustainability of farming systems.

This branch was divided in two sub-branches (**Figure 11**) : *At farm level*, to assess the autonomy of the farm and *At local context*, which aimed to assess the link of the farm with the region. The first sub branch was itself divided between *Material output* and *Labour output*.

### 3.3 LCA assessment of Polish farms

#### *Impact analysis*

The analysis of environmental impacts of 1 kg of FPCM for 2 Polish farms (PULS04 and UZ01) showed differences for all impact categories **Figure 12a**. Impacts of the UZ01 farm were always lower ( from -85% for freshwater eutrophication to -20% for human toxicity).

If we look more in detail at the contribution to climate change, per kg of FPCM (**Figure 12b**), Biogenic climate change is lower for the PULS04 farm. But climate change due to the use of fossil resources was higher, because the PULS04 farm used 5 times more fossil fuel to produce 1kg of FPCM. Therefore, the total climate change impact (biogenic, fossil and due to land use change) was lower (-50%) for the UZ01 farm.

For Freshwater eutrophication expressed in P equivalent, UZ01 farm's impact was 85% lower. Even though phosphorus is less susceptible to lixiviation than nitrogen, the huge difference of technical itinerary of the 2 farms (in one year, the PULS04 farm applied on average 70 kg of mineral phosphorus per ha when the UZ01 farm applied 2.6 kg per ha) may explained this difference.

Regarding human toxicity impact, we still had a difference but this one was less important than the other impacts ( UZ01 is at -30%). The value was expressed in CTUh (Comparative Toxic Unit for human, which expressed the estimated increase in morbidity in the total human population per unit mass of a chemical emitted: cases per kg). The PULS04 value stood at  $5.18 \times 10^{-10}$  when it was  $3.68 \times 10^{-10}$  for the UZ01 farm. If we looked in detail to the TFI (Treatment frequency index) of these 2 farms, they were quite similar for corresponding crops, and higher for UZ01 farms concerning the spring barley, winter wheat and rapeseed but these three crops were cultivated on a small percentage of the farm's surface. Moreover, the higher percentage of grasslands surfaces (which were non treated) in UZ01 farm made that the average ha of the farm received less treatment.

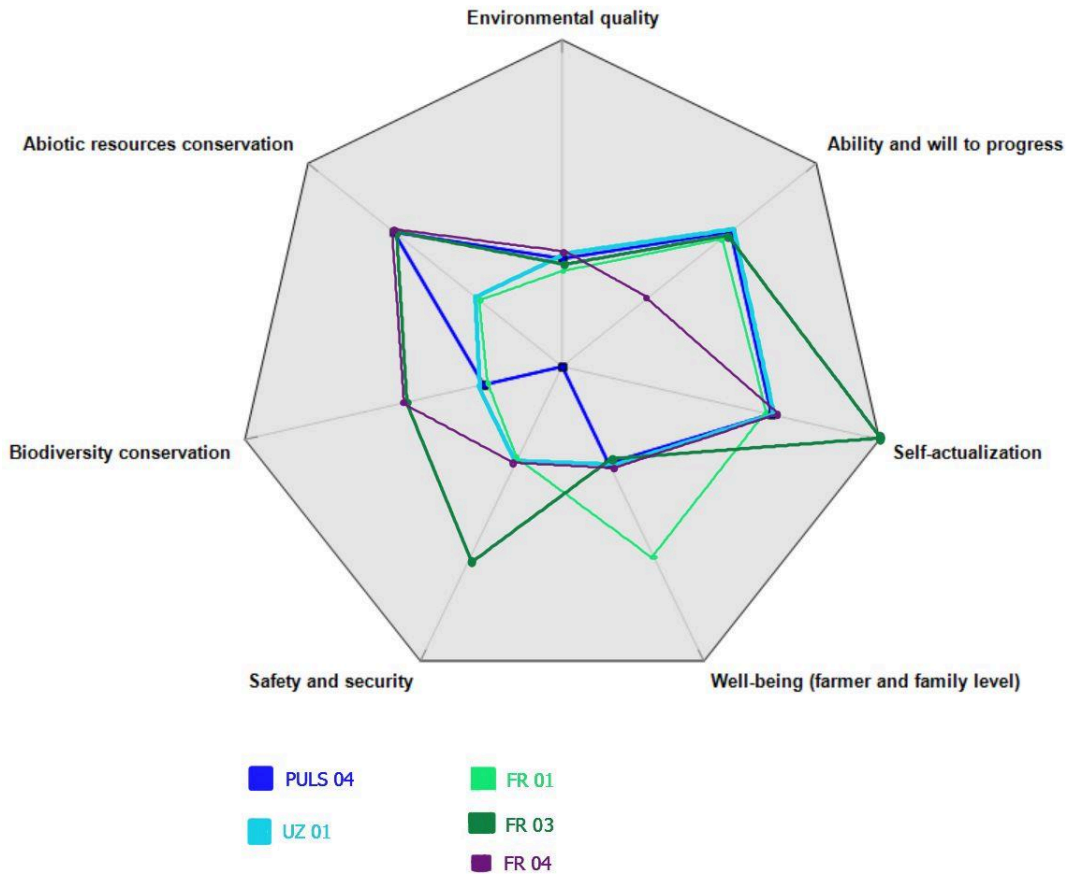


Figure 13 : Radar graph, result of the sustainability assessment at sub branch level for environmental and social dimensions  
 Analysis performed with DEXi-1-tree for 2 Polish farms (PULS04, UZ01) and 3 French farms (FR01, FR03, FR04)

SOCIAL DIMENSION	Very high					
	High			FR03		
	Medium		UZ01 FR01	FR04		
	Low		PULS04			
	Very Low					
		Very Low	Low	Medium	High	Very high
	ENVIRONMENTAL DIMENSION					

Figure 14 : Result of the DEXi-1-tre assessment of social branch versus environmental branch for the 2 Polish farms PULS04, UZ01 and French farms (FR01, FR03, FR04).

### 3.4 AMC Environmental and social assessment of Polish farms with DEXi-1 tree

#### Polish Farms Comparaison with French farms

We initially calculated all the indicators and assessed them with our reference thresholds to implement them into the DEXi.

The radar graph **Figure 13** presents the sustainability assessment results for 2 Polish farms and 3 French farms, covering the 3 environmental sub-branches: *environmental quality*, *abiotic resources conservation*, and *biodiversity conservation*; and the 4 social sub-branches: *ability and will to progress*, *self-actualization*, *well-being*, and *safety & security*.

All farms had identical scores for the sub-branch *environmental quality*. A closer examination of this sub-branch, analyzing each indicator's result, revealed a uniform assessment across all farms. This uniformity suggested that the farms shared similar strengths and weaknesses, leading to the same final result, and not different results leading to compensation at a higher level. For the other two environmental sub-branches, *abiotic resources conservation* and *biodiversity conservation*, the farms are predominantly divided into two groups. Farms FR03 and FR04 exhibited *medium to high* and *medium* sustainability, while UZ01 and FR01 ranked one class lower for these two sub-branches. Notably, PULS04 was assessed in the highest group for *abiotic resources conservation* but ranked in the lowest group for *biodiversity conservation*.

Regarding the 4 social sub-branches, there was less variation between farms for *ability and will to progress*, *self-actualization*, and *well-being*. Each time, 4 farms displayed similar scores, respectively achieving *medium to high*, *medium to high*, and *low to medium* scores. However, each sub-branch had one exception: FR04 scored lower on *ability and will to progress*, FR03 scored higher on *self-actualization*, and FR01 scored higher for *well-being*. The last social sub-branch, *safety and security*, was the one showing the most variation, with 3 farms scoring *medium to low*, PULS04 scoring *low*, and FR03 scoring *medium to high*.

At the sub-branch level, the assessment results exhibited limited variation, though there were some differences among the 5 farms. When comparing the social branch sustainability assessment scores in regard to the environmental ones (**Figure 14**), the observed differences suggested that an increase in social sustainability did not occur at the expense of environmental sustainability and vice versa.



## 4 DISCUSSION AND PROSPECT

### *First finalized DEXi tree*

The first finalized DEXi tree is notably comprehensive, yet there remain several areas for potential enhancement. The indicators selected were heavily influenced by the data collected during surveys, which constrained our choices. Indeed for this project, as it followed the Milkey one providing a basis for indicator and as the data collection took a lot of time, required data were defined early in the project in order to be able to begin the surveys early. But this has nevertheless constrained the indicator choices. For future iterations, it is crucial to refine these indicators to more accurately reflect the complexities of some criteria assessed.

Among indicators requiring improvement, we can first notice the Acute Toxicity of Pesticides. This indicator is currently measured using average LD50, which dilutes the impact of a highly toxic substance if accompanied by numerous less toxic substances. LCA indicators could be more relevant here, especially as they are performed for other indicators, and if they consider at the same time both toxicity and dose in one indicator.

Another notable indicator that could be improved is the percentage of energy produced by farms. Our case study highlighted that this indicator could be misleading. Indeed, a high value is associated with a high level of sustainability in our case. However, we encountered cases where farms relied on electricity generators powered by fossil fuels like coal, resulting in high energy autonomy but unsustainable ways to produce it. This underscores the need for a more nuanced indicator that distinguishes between renewable and non-renewable energy sources.

Also, current biodiversity indicators cover cultivated and planned biodiversity but omit associated biodiversity, which is something covered for instance in the IDEA4 method. The associated biodiversity is the proportion of biodiversity that naturally colonizes a plot via the immediate environment. It includes all the organisms (beneficial, neutral and harmful) present, in a punctual or continuous manner, in cultivated fields and adjacent semi-natural habitats (Duprat et al., 2018). It may be interesting to include or modify an indicator that integrates this associated biodiversity, which would give a more holistic view of biodiversity impacts.

In water-stressed areas, a moderate score on water consumption does not accurately reflect the high local impact, because the indicator is not adjusted with the tension on the resource. Although branch weighting helps modulate effects at interannual or regional scales, it is insufficient at very local levels. When indicators were chosen, attempts to use the CropWat model with French farms were hindered by the lack of required data, such as soil data and crop phenology. The second reluctance relies on the fact that green water is not modeled adequately.

Concerning thresholds, for terrestrial and freshwater ecotoxicity, the EF3.1 method is based on CTUe instead of 1,4-DCBeq. We couldn't make this choice because of the lack of references in current literature, as the method is quite new. The next project step will establish thresholds using this new unit by analyzing all case study farms and employing the quartile method to develop a scaling system with this new unit.

Regarding the thresholds, the ideal situation would be to establish "absolute thresholds" corresponding to the limits that our DPS must not exceed to avoid negatively impacting the local environment, similar to the planetary boundaries concept framework. However, this





approach would need to be adapted to our specific indicators and local contexts. Achieving this would require significant additional work to accurately assess the limits of local situations, and to determine what proportion of impact can be attributed to DPS among all human activities. Currently, we cannot undertake this task for our DPS, although the question of adapting the planetary boundaries framework to a smaller scale is gradually emerging (Bjørn et al., 2020). The French government has also begun such work in a recent analysis (SDES, 2023). Since we are unable for the moment to perform this delicate work, we have applied relative thresholds to differentiate between the most and least performant farms. However, it is important to keep in mind that even the best systems can have a significant environmental impact for certain indicators, while conversely, even the worst systems may not significantly impact the environment for other indicators.

Another improvement possibility is about Aggregation Rules. We could adapt more utility functions to prevent compensations among indicators, which is possible but challenging due to the tree's complexity and the number of indicators involved. It could be done if we would like to avoid compensatory effects.

Environmental impacts calculated through LCA provide an exhaustive perspective on the life cycle. However, social and economic assessments are limited to direct production stages, omitting upstream impacts such as for example, the social impact of synthetic fertilizer production, or any non farm produced product. This limitation is due to technical feasibility but remains an important point to keep in mind for the review of results or future improvements.

Then, our current scope does not include governance or institutional weight, focusing instead on farm-level decisions. While evaluating these governance impacts would be complex, especially at farm scale, as institution decisions may be one of the major drivers of some decisions taken at farm scale, this government assessment would remain an interesting avenue for future research. Expanding the link of the farm with the rest of the region or rest of the DPS sector could also provide valuable insights.

### *Second DEXi tree based on properties*

When building the new framework, we were constrained by the fact that indicators had already been chosen. If we first had selected sustainability properties, we might have opted for different indicators, possibly leading to a more exhaustive set of properties and more balanced branches in the second tree.

This new approach inspired us to consider new indicators, such as for example phosphorus circularity, which could have been included in the viability branch. Therefore, this approach based on properties seems complementary to the one based on dimensions, in order to improve the selection of indicators to ensure the most relevant ones for sustainability assessment. It is a promising framework to rethink sustainability.

Since the indicators were chosen beforehand, some, especially the social indicators, are not always perfectly adapted to the properties. For instance, our social indicators were not designed to differentiate between robustness and the ability to transform and adapt.

In this work, we also paid careful attention to the names of indicators and properties. Indeed, as highlighted in Quinlan *et al* (2016), the same properties may have different definitions depending on the field of study.



When both trees will be finalized with threshold values and utility functions, a sensitivity analysis of the trees will be performed in order to understand the weight of all indicators in the final assessment. This kind of analysis is easily performed with the IZI-EVAL R package that has been specifically developed for the DEXi Tool during the EDISC project (INRAE of Gotheron, 2023).

#### *Case study LCA and MCA analysis*

For comparison between Polish farms, we used 1kg of FPCM as a functional unit. As the choice of functional unit can impact results, we should also examine these impacts with another functional unit like for instance 1 ha of the farm.

The results indicate that several LCA indicators had similar outcomes, making it challenging to discriminate them with our current scaling. This suggests that we may need to refine the thresholds in the future to better accommodate mixed-DPS. For example, terrestrial ecotoxicity is constantly rated high across all farms, with calculated values significantly exceeding the upper threshold. All indicators of the *environmental quality* sub-branches were also identical for our assessed farms, so we may need to revise the thresholds to improve their sensibility. This is likely because mixed DPS, when assessed at the farm level, involve larger crop areas, greater use of phytosanitary products, and consequently higher terrestrial ecotoxicity compared to DPS with few crops.

Our initial results also reveal that a high level of social sustainability does not happen to the extent of the environmental ones. However, we still need to analyze the economic performances of the farms to ensure that we don't have for example a low economic sustainability which compensates for high levels of environmental and social sustainability.

For the crop data, we sometimes had records covering four years of rotation; however, we modeled our impacts based on the technical practices and yields of 2021. For dairy animals, the data are exclusively from 2021. Given that agricultural practices may vary a lot from one year to another because of climate conditions or raw material prices like mineral fertilizers, it would have been more representative to collect data over several years. This approach would ensure a more accurate reflection of the farm's performance over time and mitigate the reliance on the farmer's memory, which can introduce inaccuracies. Although efforts were made to minimize bias, like the decision to use data from 2021 instead of 2022. Indeed, the exceptional heat of 2022 makes the data non representative, but this decision also complicated data collection for farms without detailed records of their agricultural operations.

Comparing multiple countries using indicators like the TFI is also challenging due to differences in approved pesticide doses across countries. The reference dose was based on French standards when available, otherwise we tried to refer to the legal dose specified by suppliers. Introducing a new indicator, such as the 'I-Phy' from Pierlot et al (2023), could improve comparability, though it requires more complex calculations and extensive data.

To date, we have not conducted an uncertainty analysis of the LCAs to evaluate their precision. Conducting such analysis would be particularly valuable when comparing different farms. Especially if results are closed between two farms, it could help us to identify areas for improvement.

Searchers studying MCA sustainability of diversified organic cropping systems found that it helps to reach a high sustainability in environmental dimension due to reduction of fertilizers and pesticides (Rodriguez et al., 2021). But they also underline in this study that limited access to knowledge, technology and market for minor crops, and the concern of farmers about the consistency of policies was a barrier for crop diversification. Therefore, in a mixed farming system like those of the DairyMix project the concern of the market for minor crops can be avoided if the crops produced are used to feed the herd and then enhance the circularity between crops and animal production.



## 5 CONCLUSION

The finalization of the environmental branch weightings reveals only minor differences between the choices made in the two countries Poland and France. However, the few disparities, particularly regarding water, will be valuable to discuss with our partners.

The new DEXi framework, based on properties, offers new perspectives for rethinking sustainability assessment frameworks. This approach appears to complement the dimension-based approach, and then, for the future, this framework offers an inspiration guide in the selection of the most relevant indicators for a holistic sustainability assessment.

Regarding the LCA study of the two Polish farms, the initial case studies show significant contrasts in terms of impacts. Therefore, it will be crucial in the next steps of the work to thoroughly examine the specific mechanisms and reasons behind these differences.

The initial results of the economic and environmental MCA assessments of the Polish and French farms are also noteworthy. They indicate that some current thresholds may require further adjustment to be perfectly suited for mixed DPS assessment. Although the initial results from these five farms are not highly contrasted and we are still awaiting economic assessment, they currently suggest that mixed-DPS with higher environmental sustainability did not achieve this at the expense of social sustainability. On the contrary, they appear to be complementary.

The next step of this project will involve assessing the remaining 23 farms. With this broader sample, we will re-adjust the thresholds for the most sensitive indicators, for which we currently lack sufficient data. Ultimately, the assessment of this panel of farms will allow us to thoroughly analyze the trade-offs and synergies in sustainability. Additionally, when finalized with corresponding weights, the second DEXi tree will enable us to explore the impact of the tree structure on the upper-level assessment results.

## Bibliography references:

- Baillet, V., Balaine, L., Díaz De Otálora, X., Rodriguez, D. G. P., Frączak-Müller, J., Flø, B. E., Amon, B., Alem, H., Anestis, V., Bartzanas, T., Breen, J., Buckley, C., Castellan, E., Dach, J., Dragoni, F., Johansen, A., Jørgensen, G., Krol, D., Lien, G., ... Wilfart, A. (2022). *Dexi-Dairy indicator handbook—Sustainability tree and selected indicators for assessing European specialised dairy farms* [jeu de données]. Recherche Data Gouv. <https://doi.org/10.57745/XEPNUH>
- Bakken, A. K., Daugstad, K., Johansen, A., Hjelkrem, A.-G. R., Fystro, G., Strømman, A. H., & Korsath, A. (2017). Environmental impacts along intensity gradients in Norwegian dairy production as evaluated by life cycle assessments. *Agricultural Systems*, 158, 50-60. <https://doi.org/10.1016/j.agsy.2017.09.001>
- Bjørn, A., Chandrakumar, C., Boulay, A.-M., Doka, G., Fang, K., Gondran, N., Hauschild, M. Z., Kerkhof, A., King, H., Margni, M., McLaren, S., Mueller, C., Owsianiak, M., Peters, G., Roos, S., Sala, S., Sandin, G., Sim, S., Vargas-Gonzalez, M., & Ryberg, M. (2020). Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. *Environmental Research Letters*, 15(8), 083001. <https://doi.org/10.1088/1748-9326/ab89d7>
- Bockstaller, C., Guichard, L., Makowski, D., Aveline, A., Girardin, P., & Plantureux, S. (2008). Agri-environmental indicators to assess cropping and farming systems. A review. *Agronomy for Sustainable Development*, 28(1), 139-149. <https://doi.org/10.1051/agro:2007052>
- Bohanec, M. (2008). *DEXi : Program for Multi-Attribute Decision Making User's Manual*.
- Bohanec, M. (2021). *DEXi : Program for Multi-Attribute Decision Making User's Manual*.
- Briquel, V., Vilain, L., Bourdais, J., Girardin, P., Mouchet, C., & Viaux, P. (2001). *La méthode IDEA (indicateurs de durabilité des exploitations agricoles) : Une démarche pédagogique*. [https://www.semanticscholar.org/paper/La-m%C3%A9thode-IDEA-\(indicateurs-de-durabilit%C3%A9-des-%3A-Briquel-Vilain/fdd463c5beb081e453f9a3a074b78551862edd66](https://www.semanticscholar.org/paper/La-m%C3%A9thode-IDEA-(indicateurs-de-durabilit%C3%A9-des-%3A-Briquel-Vilain/fdd463c5beb081e453f9a3a074b78551862edd66)
- Britz, W., & Kuhn, T. (2014). *A highly detailed template model for dynamic optimization of farms*. <https://www.semanticscholar.org/paper/A-highly-detailed-template-model-for-dynamic-of-Britz-Kuhn/e84afdc2bd81848ccf478a1fec8fba648a0f1962>
- Campbell, B., Beare, D., Bennett, E., Hall-Spencer, J., Ingram, J., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J., & Shindell, D. (2017). Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society*, 22(4). <https://doi.org/10.5751/ES-09595-220408>
- CAP2ER. (2022). *CAP'2ER® : Guide simplifié de la méthodologie d'évaluation environnementale d'une exploitation agricole*. [https://abiodoc.docressources.fr/index.php?lvl=notice\\_display&id=46592](https://abiodoc.docressources.fr/index.php?lvl=notice_display&id=46592)
- Caro, T., Rowe, Z., Berger, J., Wholey, P., & Dobson, A. (2022). An inconvenient misconception : Climate change is not the principal driver of biodiversity loss. *Conservation Letters*, 15(3), e12868. <https://doi.org/10.1111/conl.12868>
- Chapman, J., Power, A., Chandra, S., & Cozzolino, D. (2019). Meat Consumption and Green Gas Emissions : A Chemometrics Analysis. *Food Analytical Methods*, 12(2), 469-474.

- <https://doi.org/10.1007/s12161-018-1378-8>
- Colomb, V., Amar, S. A., Mens, C. B., Gac, A., Gaillard, G., Koch, P., Mousset, J., Salou, T., Tailleur, A., & Werf, H. M. G. van der. (2015). AGRIBALYSE®, the French LCI Database for agricultural products : High quality data for producers and environmental labelling. *OCL*, 22(1), Article 1. <https://doi.org/10.1051/ocl/20140047>
- Craheix, D., Angevin, F., Bergez, J.-E., Bockstaller, C. C., Colomb, B. B., Guichard, L. L., Reau, R., & Doré, T. (2012). *MASC 2.0, un outil d'évaluation multicritère pour estimer la contribution des systèmes de culture au développement durable*. *Innovations Agronomiques* 20, 35-48. <https://doi.org/10.17180/BX81-1X20>
- Craheix, D., Bergez, J.-E., Angevin, F., Bockstaller, C., Bohanec, M., Colomb, B., Doré, T., Fortino, G., Guichard, L., Pelzer, E., Méssean, A., Reau, R., & Sadok, W. (2015). Guidelines to design models assessing agricultural sustainability, based upon feedbacks from the DEXi decision support system. *Agronomy for Sustainable Development*, 35(4), 1431-1447. <https://doi.org/10.1007/s13593-015-0315-0>
- Darnhofer, I. (2014). Resilience and why it matters for farm management. *European Review of Agricultural Economics*, 41(3), 461-484. <https://doi.org/10.1093/erae/jbu012>
- Del Prado, A., Misselbrook, T. H., Chadwick, D. R., Hopkins, A., Dewhurst, R. J., Davison, P., Butler, A., Turner, M., Schroder, J., & Scholefield, D. (2006). *SIMSDAIRY - a modelling framework to identify new integrated dairy production systems* [Software]. <https://repository.rothamsted.ac.uk/item/85v5w/simsdairy-a-modelling-framework-to-identify-new-integrated-dairy-production-systems>
- Duprat, P., Thiechart, M., & Sarthou, J.-P. (2018). *Biodiversité associée : Définition Dictionnaire d'agroécologie*. INRAE. <https://doi.org/10.17180/6WBE-T019>
- European Commission. (2018). *PEFCR Guidance document,—Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3*. [https://green-business.ec.europa.eu/environmental-footprint-methods\\_en](https://green-business.ec.europa.eu/environmental-footprint-methods_en)
- FAO. (2014). *SAFA guidelines : Sustainability assessment of food and agriculture systems* (N. Scialabba, Food and Agriculture Organization of the United Nations, & Food and Agriculture Organization of the United Nations, Éd.s.; Version 3.0). Food and Agriculture Organization of the United Nations.
- Hani, F., Braga, F. S., Stampfli, A., Keller, T., Fischer, M., & Porsche, H. (Éds.). (2003). RISE, a Tool for Holistic Sustainability Assessment at the Farm Level. *International Food and Agribusiness Management Review*. <https://doi.org/10.22004/ag.econ.34379>
- Holster, H. (2013). *KringloopWijzer, goed geborg!?*
- International Dairy Federation. (2015). *A common carbon footprint approach for the dairy sector : The IDF guide to standard life cycle assessment methodology*.
- IPCC. (2021). *Climate Change 2021 : The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. Doi:10.1017/9781009157896. (1<sup>re</sup> éd.). <https://doi.org/10.1017/9781009157896>
- ISO. (2006). *ISO 14040:2006*. ISO. <https://www.iso.org/fr/standard/37456.html>
- Jennings, J., Day, P., Phelps, C., & Packham, R. (2006). Improving natural resource



- management by “thinking industry and acting regionally” : Introduction and successes of dairy Australia’s multi-scaled natural resource management strategy. In *Changing European farming systems for a better future* (p. 409-413). Wageningen Academic.  
[https://doi.org/10.3920/9789086865727\\_099](https://doi.org/10.3920/9789086865727_099)
- Lairez, J., Feschet, P., Aubin, J., Bockstaller, C., & Bouvarel (Coord.), I. (2016). *Agriculture et développement durable : Guide pour l'évaluation multicritère*. Educagri Editions.
- Lampridi, M. G., Sørensen, C. G., & Bochtis, D. (2019). Agricultural Sustainability : A Review of Concepts and Methods. *Sustainability*, 11(18), Article 18.  
<https://doi.org/10.3390/su11185120>
- Lewandowski, I., Härdtlein, M., & Kaltschmitt, M. (1999). Sustainable Crop Production : Definition and Methodological Approach for Assessing and Implementing Sustainability. *Crop Science*, 39(1), crops1999.0011183X003900010029x.  
<https://doi.org/10.2135/crops1999.0011183X003900010029x>
- Loyon, L. (2018). Overview of Animal Manure Management for Beef, Pig, and Poultry Farms in France. *Frontiers in Sustainable Food Systems*, 2.  
<https://doi.org/10.3389/fsufs.2018.00036>
- Malagó, A., & Bouraoui, F. (2023). Forty years of anthropogenic nutrient pressures : Agriculture and domestic nitrogen and phosphorus inventory in view of sustainable nutrient management. *Frontiers in Sustainable Food Systems*, 7.  
<https://doi.org/10.3389/fsufs.2023.1062435>
- Meul, M., Van Passel, S., Nevens, F., Dessein, J., Rogge, E., Mulier, A., & Van Hauwermeiren, A. (2008). MOTIFS : A monitoring tool for integrated farm sustainability. *Agronomy for Sustainable Development*, 28(2), 321-332.  
<https://doi.org/10.1051/agro:2008001>
- PEF. (2013). EU: Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. In *OJ L* (Vol. 124).  
<http://data.europa.eu/eli/reco/2013/179/oj/eng>
- Pelzer, E., Fortino, G., Bockstaller, C., Angevin, F., Lamine, C., Moonen, C., Vasileiadis, V., Guérin, D., Guichard, L., Reau, R., & Messéan, A. (2012). Assessing innovative cropping systems with DEXiPM, a qualitative multi-criteria assessment tool derived from DEXi. *Ecological Indicators*, 18, 171-182.  
<https://doi.org/10.1016/j.ecolind.2011.11.019>
- Pierlot, F., Marks-Perreau, J., Soulé, E., Keichinger, O., Bedos, C., Prevost, L., Van Dijk, P., & Bockstaller, C. (2023). An indicator to assess risks on water and air of pesticide spraying in crop fields. *Science of The Total Environment*, 870, 161000.  
<https://doi.org/10.1016/j.scitotenv.2022.161000>
- Poux, X., & Aubert, P.-M. (2018). *An agroecological Europe in 2050 : Multifunctional agriculture for healthy eating*.
- Quinlan, A. E., Berbés-Blázquez, M., Haider, L. J., & Peterson, G. D. (2016). Measuring and assessing resilience : Broadening understanding through multiple disciplinary perspectives. *Journal of Applied Ecology*, 53(3), 677-687.  
<https://doi.org/10.1111/1365-2664.12550>
- RAD. (2010). *(Reseau d'Agriculture Durable) LE DIAGNOSTIC DE DURABILITE Guide de l'utilisateur*.
- Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M.,

- Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., ... Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, 9(37), eadh2458. <https://doi.org/10.1126/sciadv.adh2458>
- Rigolot, C., Baratte, C., Rellier, J.-P., Raison, C., Poupa, J.-C., & Faverdin, P. (2007). *MELODIE : A Whole-Farm Model To Study The Dynamics Of Nutrients In Integrated Dairy And Pig Farms*.
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., ... Foley, J. A. (2009). A safe operating space for humanity. *Nature*, 461(7263), 472-475. <https://doi.org/10.1038/461472a>
- Rodriguez, C., Dimitrova Mårtensson, L.-M., Zachrisson, M., & Carlsson, G. (2021). Sustainability of Diversified Organic Cropping Systems—Challenges Identified by Farmer Interviews and Multi-Criteria Assessments. *Frontiers in Agronomy*, 3. <https://doi.org/10.3389/fagro.2021.698968>
- Roer, A.-G., Johansen, A., Bakken, A. K., Daugstad, K., Fystro, G., & Strømman, A. H. (2013). Environmental impacts of combined milk and meat production in Norway according to a life cycle assessment with expanded system boundaries. *Livestock Science*, 155(2), 384-396. <https://doi.org/10.1016/j.livsci.2013.05.004>
- Sadok, W., Angevin, F., Bergez, J.-E., Bockstaller, C., Colomb, B., Guichard, L., Reau, R., Messéan, A., & Doré, T. (2009). MASC, a qualitative multi-attribute decision model for ex ante assessment of the sustainability of cropping systems. *Agronomy for Sustainable Development*, 29(3), 447-461. <https://doi.org/10.1051/agro/2009006>
- SDES. (2023). *Commissariat général au développement, La France face aux neuf limites planétaires*. La France face aux neuf limites planétaires. <https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/la-france-face-aux-neuf-limites-planetaires/livre>
- Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries : Guiding human development on a changing planet. *Science*, 347(6223), 1259855. <https://doi.org/10.1126/science.1259855>
- Thoma, G., Berndt, A., Wang, Y., Becona, G., Bertrand, S., Groot, J., Dollé, J., Dong, H., Faverdin, P., Flysjö, A., Gac, A., Garg, M., Gollnow, S., Naón, J., Kulov, S., Ledgard, S., Lieffering, M., Lukuyu, B., Meale, S., & Wiedemann, S. (2016). *Environmental performance of large ruminant supply chains : Guidelines for assessment. Version 1* (FAO). <https://doi.org/10.13140/RG.2.2.30820.99203>
- Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W. H., Simberloff, D., & Swackhamer, D. (2001). Forecasting Agriculturally Driven Global Environmental Change. *Science*, 292(5515), 281-284. <https://doi.org/10.1126/science.1057544>
- Trigo, A., Marta-Costa, A., & Fragoso, R. (2021). Principles of Sustainable Agriculture : Defining Standardized Reference Points. *Sustainability*, 13(8), Article 8. <https://doi.org/10.3390/su13084086>
- UN-WCED, U. (1987). *Report of the World Commission on Environment and Development :*

- Note /: by the Secretary-General. <https://digitallibrary.un.org/record/139811>
- Velten, S., Leventon, J., Jager, N., & Newig, J. (2015). What Is Sustainable Agriculture? A Systematic Review. *Sustainability*, 7(6), Article 6. <https://doi.org/10.3390/su7067833>
- Vilain, L., Boisset, K., Girardin, P. P., Guillaumin, A., Mouchet, C., Viaux, P., & Zahm, F. (2008). *La méthode IDEA : Indicateurs de durabilité des exploitations agricoles : guide d'utilisation* (p. 162 p.). Educagri Editions. <https://hal.inrae.fr/hal-02824983>
- Wilfart, A., Baillet, V., Balaine, L., de Otálora, X. D., Dragoni, F., Krol, D. J., Frątczak-Müller, J., Rychła, A., Rodriguez, D. G. P., Breen, J., Anestis, V., Buckley, C., Alem, H., Winiwarter, W., Akkal-Corfini, N., & Amon, B. (2023). DEXi-Dairy : An ex post multicriteria tool to assess the sustainability of dairy production systems in various European regions. *Agronomy for Sustainable Development*, 43(6), 82. <https://doi.org/10.1007/s13593-023-00935-3>
- Zham, F., Girard, S., Alonso Ugaglia, A., Barbier, J.-M., Boureau, H., Crayon, D., Cohen, S., Del'homme, B., Gafsi, M., Gasselin, P., Gestin, C., Guichard, L., Loyce, C., Manneville, V., Redlingshöfer, B., & Rodriguez, I. (2023). *La méthode IDEA - Indicateurs de durabilité des Exploitations Agricoles. Principes & guide d'utilisation. Évaluer la durabilité de l'exploitation agricole*, Educagri éditions.

## Appendix

Appendix 1 Table of indicator description:

Indicators	LCA	New	Description
<i>Freshwater ecotoxicity</i>	v	v	LCA midpoint impact category. It expresses the fraction of aquatic species potentially affected by chemicals, integrated as a function of time and volume per unit mass of chemical molecules emitted.
<i>Number of different cultivated species</i>	x	v	It is the number of species cultivated on a farm without taking account of the species varieties. A high level is favorable to the biodiversity as this increases the continuity of food, resources for reproduction, soil cover with a better management of the pest and disease with less pesticides applied.
<i>Crop water consumption</i>	x	v	This indicator assesses the water irrigation that is needed to grow a crop (m <sup>3</sup> /ha).
<i>Sobriety in the use of Phosphorus</i>	x	v	It is the average of mineral phosphorus (P <sub>2</sub> O <sub>5</sub> ) applied for one year on the Utilized Agricultural Area (UAA) of the farm (kg P <sub>2</sub> O <sub>5</sub> /ha/year).
<i>Field size</i>	x	v	The field size (in ha) is the mean of the field size present on the farm. The smaller a field is the higher side number it has which means more interfaces with some non-arable land favorable for biodiversity.
<i>Habitat diversity</i>			The habitat diversity is the number of type of habitat (arable land, pond, forest, etc.) that are present on the farm. A high number of habitat type provides more shelter, food and resources for the life cycle of the organism living in the agroecosystem
<i>Percentage of semi natural habitat</i>	x	v	It is the percentage of semi-natural habitats (pond, forest, etc.) on the farm (%).
<i>Number of family crop</i>	x	v	This indicator favors a high number of family crops because the crop cycle could be quite different from a family crop to another in matter of growing time, biomass product and flowering for dicotyledon species. If a farmer includes different family crops in his rotation, he will increase the continuity of food and resources temporally and spatially in his farm.
<i>Percentage of grassland excluded from rotation</i>	x	v	The percentage of grassland excluded from the crop rotation is the percentage of grassland that is not included in a crop rotation. These grasslands are usually kept at least six or seven years in a row before being plough. Keeping the grassland for a long period is very beneficial for the biodiversity at several levels: less physical and chemical disturbances (soil tillage, fertilizer application); the soil quality is improved; permanent soil coverage, food continuity, etc.).
<i>Tillage intensity</i>	x	v	This indicator corresponds to the soil tillage intensity in matter of depth and animation. The deeper the soil tillage the more damageable, it will be for the soil. For the animation, this depends on the type of tool used (row crop cultivator, harrow, rotative harrow, etc.).
<i>Total nitrogen input</i>	x	v	This indicator is the level of nitrogen that is applied on a field whatever the type of fertilization i.e. mineral or organic (N kg/ha). A high level of nitrogen will be unfavorable for the biodiversity as this can disturb the nitrogen cycle and/or the balance in the microorganism communities.
<i>Type of fertilizer</i>	x	v	This indicator characterized the type of fertilizer applied on the field i.e. mineral or organic fertilizer and within the organic fertilizers, we distinguish the slurry which is very close to the mineral fertilizer in terms of nitrogen release. The organic fertilizers except the slurry are better than the mineral fertilizers because the elements are released slowly to the soil that mitigate the unbalance of the chemical cycles.
<i>Erosion risk</i>	x	x	It refers to the potential of eroded soil per hectare (ha) of the farm under study over the production year (t of eroded soil /ha). Precipitation, soil type, crop management and topography influence it

<i>Heavy metal balance</i>	v	x	This indicator calculates the difference between inputs and outputs of heavy metals. It takes into account the atmospheric feedback of heavy metal components from fertilizers, seeds, and phytosanitary products. This measure represents the remaining heavy metals in the soil and is thus an indirect indicator of soil toxicity (kg 1,4-dichlorobenzene (1,4-DB)eq / kg FPCM)
<i>Eutrophication potential</i>	v	x	It evaluates the direct impact of excess nitrogen (N) and phosphorus (P) inputs on water quality. This measure is given in kg of phosphate (PO <sub>4</sub> <sup>3-</sup> ) equivalent (eq) per Functional Unit which could be for our DPS to produce one kilo of Fat and Protein Corrected Milk (FPCM).
<i>Air acidification</i>	v	x	This indicator measures the potential impact of acidifying pollutants through the LCA method. The major acidifying pollutants considered are sulfur dioxide (SO <sub>2</sub> ), nitrogen (mono/di) oxide (NO <sub>x</sub> ), and ammonia (NH <sub>3</sub> ). It is expressed in kg SO <sub>2</sub> eq/ kg FPCM
<i>Global warming potential</i>	v	x	This indicator is based on the global warming potential (GWP) measure developed by the IPCC. It quantifies GHG emitted by the dairy system. This measure is given in kg of carbon dioxide (CO <sub>2</sub> ) equivalent per functional unit.
<i>Water consumption of the dairy herd</i>	x	x	This indicator estimates water consumption of the dairy herd per functional unit produced (L/kg FPCM). It includes drinking and cleaning water during housing and grazing periods.
<i>Total energy consumption</i>	v	x	This indicator measures the farm's energy consumption, both direct and indirect, per kg of FPCM produced (MJ/kg FPCM). Direct energy consumption encompasses all energy used for on-farm processes (e.g., crop management, heating in buildings and electricity in barns). Indirect energy consumption takes into account all energy used for the production of off-farm inputs (e.g., off-farm feed production, diesel production).
<i>Percentage of farm energy production in the total energy use</i>	x	x	This indicator measures the percentage of energy produced on the farm. It includes direct and indirect energy consumption.
<i>crop rotation diversity</i>	x	x	Number of crop species (arable crop or grassland) which composes the crop rotation. The diversity of species within a rotation is known to improve the soil quality with the different types of roots and the management differentiation that can provide organic matter with the crop residues.
<i>Treatment frequency index</i>	x	x	This indicator is based on the amount of pesticides applied by farmers on their agricultural plots over the production year. For each phytosanitary product, a certified standard dose is defined per ha and crop type according to the product's technical guidelines. This indicator gives the number of treatments equivalent to full rates and full field application. It is equal to 1 if the farmer uses the standard dose.
<i>Acute toxicity of pesticide</i>	x	x	This indicator refers to pesticide toxicity based on the Pesticide Properties Database (PPDB) and technical information from World Health. It averages acute toxicity levels of active substances applied on farms. The acute toxicity level of a substance is defined by its Lethal Dose median (LD50), i.e., the amount of substance given all at once, which subsequently causes the death of 50% of a group of test animals within a given period.
<i>Presence of multi annual crop in the rotation</i>	x	v	This indicator assesses the presence of grassland or other multiannual crops in the rotation. The presence of grassland in a rotation favors the biodiversity as this crop stays for a longer period and thus provides shelter and food during critical periods of the year for the organisms
<i>Grassland excluded from the rotation management</i>	x	x	This indicator evaluates the ecological value of grasslands based on management and fertilization strategies. Depending on these two characteristics, grasslands can be important shelters for biodiversity. Grasslands are given a score depending on the management intensity (grazing, mowing) and fertilization strategy (mineral or organic fertilizer, level of mineral fertilizer).

## Appendix 2 New indicators thresholds:



Indicator	Unit	Thresholds	Reference
<i>Freshwater ecotoxicity</i>	1-4DCBeq / kgFPCM	<0,0025	Ref value : (Bakken et al., 2017) for 7 Norway farms Scale: expert decision
		[0,0025 ; 0,005]	
		>0,005	
<i>Terrestrial ecotoxicity</i>	1-4DCBeq / kgFPCM	< 0,0028	Ref value (Roer et al., 2013) on 3 farms scale : expert decision
		[ 0,0028 ; 0,0036 ]	
		>0,0036	
<i>Number of different cultivated species</i>	Number of productive cultivated species	[1; 2 ]	IDEA4 p 123
		[ 3 ; 4 ]	
		>= 6	
<i>Crop water consumption</i>	Amount of water in m3 / year	< 200	IDEA4 p 160
		[ 200 ; 10 000 [	
		[ 10 000 ; 30 000 [	
		> 30 000	
<i>Sobriety in the use of Phosphorus</i>	kg Mineral P (P2O5) applied / UAA ha	> 60	IDEA4 p 163
		] 40 ; 60 ]	
		] 30 : 40 ]	
		] 20 ; 30 ]	
		< 20	
<i>Field size</i>	% of surface of fields > 12 ha	0	IDEA4 p136
		] 0; 0,15]	
		] 0,15 ; 0,30 ]	
		> 0,3	
<i>Percentage of semi natural habitat</i>	% of the UAA	[0; 0,15]	Expert decision
		] 0,15 ; 0,30 [	
		> 30	
<i>Number of family crop</i>	Number of family crops	1	IDEA4
		2 ou 3	
		4 ou 5	
		>6	
<i>Percentage of grassland excluded from rotation</i>	% grassland	<30	Expert decision
		[30 ; 60]	
		> 60	

<i>Tillage intensity</i>	Qualitative indicator, most common practices	No tillage : low	Expert decision
		Harrow: medium	
		Ploughing :high	
<i>Total nitrogen input</i>	kg N /ha	<50	Expert decision
		[ 50 ; 150 ]	
		> 150	
<i>Type of fertilizer</i>	% of organic N in total N applied	<50	Expert decision
		[ 50 ; 80 ]	
		> 80	
<i>Presence of multi annual crop in the rotation</i>	binary option	Yes	Expert decision
		No	

### Appendix 3 Table of indicator assessment of case study farms with the DEXi-1-tree

Option	PULS04	UZ01	FR01	FR03	FR04
Eutrophication (CML)	Low	Low	Low	Low	Low
Freshwater ecotoxicity	High	Medium	High	High	High
Global warming potential	High	High	High	High	High
Air acidification	Very high	Medium	Very high	High	Very high
Erosion risk	very low	very low	very low	very low	very low
Heavy metal balance	Low	Low	Low	Low	Low
Crop rotation diversity	Medium to high	Low to medium	Low to medium	Medium to high	Low to medium
Terrestrial ecotoxicity	High	High	High	High	High
Water consumption of the dairy herd	High	High	Low	Low	Low
Crop water consumption	Low	Low	Low	Low	Low
Total energy consumption	Very high	Low	Medium	Medium	Medium
% of farm energy production in the total energy use	Very High	very low	very low	Very High	very low
Sobriety in the use of phosphorus	Very high	very Low	very Low	very Low	low
Habitat diversity	High	Medium	Low	Medium	Medium
Percentage of semi-natural habitats	Low	Low	Low	Low	Low
Field size	High	None	Medium	None	Low
Number of different cultivated species	Low	High	High	High	High
Number of crop family	Medium to low	Medium to high	Medium to low	Medium to low	Medium to low
Percentage of grassland excluded from the crop rotation	Low	Medium	Low	Low	Low
Tillage intensity	High	High	High	High	High
Total nitrogen input	High	High	Medium	High	High
Percentage of organic fertilizer	Medium	Medium	Low	Low	High
Treatment frequency index	Low	Medium	Medium	Medium	Medium
Acute toxicity	Low	Low	Low	Low	Low
Presence of multiannual crops in the rotation	No	No	Yes	Yes	Yes
Grassland (excluded from the rotation management)	High	Medium	Medium	Low	Low
Health protection	Low	Low	Medium	Medium	Medium
Social welfare and safety	Medium	Low	Low	High	Medium
Work support	Low	Medium	Low	High	Medium
Risk of accidents	Medium	Medium	Medium	Medium	High
Financial security	Low	Medium	Low	High	High
Savings	Low	High	High	High	Low
Access to services and institutions	Low	Medium	Low	Low	Low
Family and friend quality time	Low	Low	Low	High	High
Loneliness	Low	Low	Low	Low	Medium
Free time	Low	Low	Low	High	High
Social relations with farmers	Low	Low	Medium	Low	Low
Social engagement	Low	Low	Medium	Medium	Medium
Job satisfaction	Medium	Medium	Medium	High	Medium
Pride of being a farmer	Medium	Medium	Medium	Medium	Medium
Self-control at work	Low	High	Low	Medium	Medium
Investments	Low	Low	Medium	High	Low
Farm continuation	High	High	Medium	Low	High
Attitude to sustainable practices	Low	Low	Medium	Medium	Low
Motivation for changes in production	Medium	Medium	Low	Medium	Low



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Titre français : Conception et étude de cas d'une analyse multicritère de la durabilité des systèmes de polyculture élevage laitiers Titre anglais : Conceptual and case study multi criteria sustainability assessment of dairy mix farming systems	
<p>Abstract : Current sustainability assessment tools for farming systems fall short in accurately evaluating mixed dairy production systems across Europe. They are often either specific to certain geographical contexts, specialized in crop or cattle assessment, are not exhaustive in assessing the 3 dimensions of sustainability (environmental, social, and economic impacts), or are too general to accurately assess mixed dairy production systems.</p> <p>This work, part of the European DairyMix project, first details the finalization of a multi-criteria sustainability assessment tool based on DEXi software. This tool incorporates indicators from the three sustainability dimensions: social, environmental, and economic. Second part of this work describes the development of a new conceptual assessment framework that uses the same tools and indicators, but organizes them by sustainability properties. The final part presents a case study assessing the environmental and social dimensions of two Polish farms using the first finalized tool.</p> <p>The property-based DEXi framework offers new perspectives for sustainability assessment, complementing traditional dimension-based approaches. Preliminary results from these case study farms suggest that higher environmental sustainability in mixed dairy production systems does not compromise social sustainability. Future work will involve assessing additional farms to refine indicators and comprehensively analyze sustainability trade-offs and synergies.</p>	
<p>Résumé : Les outils actuels d'évaluation de la durabilité des systèmes agricoles ne permettent pas d'évaluer avec précision les systèmes mixtes de production laitière en Europe. Ils sont souvent spécifiques à certains contextes géographiques, spécialisés dans l'évaluation des cultures ou des troupeaux, ne sont pas exhaustifs dans l'évaluation des trois dimensions de la durabilité (impacts environnementaux, sociaux et économiques), ou sont trop généraux pour évaluer avec précision les systèmes mixtes de production laitière.</p> <p>Ce travail, qui fait partie du projet européen DairyMix, détaille d'abord la finalisation d'un outil d'évaluation multicritère de la durabilité basé sur le logiciel DEXi. Cet outil incorpore des indicateurs des trois dimensions de la durabilité : sociale, environnementale et économique. La deuxième partie de ce travail décrit le développement d'un nouveau cadre d'évaluation conceptuel qui utilise les mêmes outils et indicateurs, mais les organise en fonction des propriétés de la durabilité. La dernière partie présente une étude de cas évaluant les dimensions environnementales et sociales de deux exploitations agricoles polonaises à l'aide du premier outil finalisé.</p> <p>Le cadre DEXi basé sur les propriétés offre de nouvelles perspectives pour l'évaluation de la durabilité, en complément des approches traditionnelles basées sur les dimensions. Les résultats préliminaires de ces études de cas suggèrent qu'une plus grande durabilité environnementale dans les systèmes mixtes de production laitière ne compromet pas la durabilité sociale. Les travaux futurs consisteront à évaluer d'autres exploitations afin d'affiner les indicateurs et d'analyser de manière exhaustive les compromis et les synergies en matière de durabilité.</p>	
Mots-clés : Evaluation multicritères, propriétés de durabilité, systèmes mixtes de production laitière, indicateur Key Words: Multi criteria assessment, sustainability properties, mixed dairy production systems, indicator	