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Whole-Systems Analysis of Environmental and Economic Sustainability in Arable Cropping Systems: A Case Study

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Abstract: The long-term sustainability of crop production depends on the complex network of interactions and trade-offs between biotic, abiotic and economic components of agroecosystems. An integrated arable management system was designed to maintain yields, whilst enhancing biodiversity and minimising environmental impact. Management interventions included conservation tillage and organic matter incorporation for soil biophysical health, reduced crop protection inputs and integrated pest management strategies for enhanced biodiversity and ecosystem functions, and intercropping, cover cropping and under-sowing to achieve more sustainable nutrient management. This system was compared directly with standard commercial practice in a split-field experimental design over a six-year crop rotation. The effect of the cropping treatment was assessed according to the responses of a suite of indicators, which were used to parameterise a qualitative multi-attribute model. Scenarios were run to test whether the integrated cropping system achieved greater levels of overall sustainability relative to standard commercial practice. Overall sustainability was rated high for both integrated and conventional management of bean, barley and wheat crops. Winter oilseed crops scored medium for both cropping systems and potatoes scored very low under standard management but achieved a medium level of sustainability with integrated management. In general, high scores for environmental sustainability in integrated cropping systems were offset by low scores for economic sustainability relative to standard commercial practice. This case study demonstrates the value of a ‘whole cropping systems’ approach using qualitative multi-attribute modelling for the assessment of existing cropping systems and for predicting the likely impact of new management interventions on arable sustainability.

Keywords: integrated farm management; long-term platform; biodiversity; DEXi

1. Introduction

Modern agriculture faces the challenge of simultaneously producing healthy food, adapting to climate change, protecting natural resources and conserving biodiversity [1]. Designing crop systems to achieve these multiple goals, combining both improved productivity and sustainability, is a complex decision problem with synergies, trade-offs and conflicts between the different elements of the system [2,3]. Although there has been an increase in research and application of management interventions to try to address these multiple goals [4], the focus tends to be on specific components of the system tested in isolation (e.g., tillage practices, crop diversification, biodiversity conservation or pest and disease management) and there is little empirical evidence for their efficacy at a whole-system scale [5]. This is problematic since management to improve one component could have a negative impact on a different part of the system. A more holistic approach is therefore required, for which the

evaluation must consider both economic and environmental impacts and account for positive, negative and neutral effects resulting from trade-offs and interactions between different elements. Economic, ecological and environmental data come in a diversity of forms and are rarely directly comparable through the same metrics [6]. Nevertheless, assessment of the overall sustainability of commercial agricultural systems is necessary to identify opportunities for improvement and to enable the iterative development of more sustainable farming practices.

Qualitative multicriteria evaluation methods provide one possible solution [1]. An example of such a tool is a multi-attribute decision model (MADM) that can combine qualitative and quantitative data in a single modelling framework. The structure and rationale of the multi-attribute modelling approach is fully explained in [7,8]. Briefly, overall sustainability is broken down into several smaller dimensions (e.g., economic, environmental and social sustainability) and these in turn are simplified further into increasingly more quantifiable component parts. Each dimension represents a hierarchy of objectives organised into a tree-like structure ending with leaves or terminal nodes, which are the input variables (indicators). Aggregating a suite of indicators into a single index in this way provides a more comprehensive holistic assessment of sustainability than assessments based on individual indicators measured in isolation, due to the inter-dependence and potential functional redundancy between variables [9]. This approach also allows identification of trade-offs between elements within the system, e.g., where an expected positive effect of a change in management might be offset by a negative impact elsewhere. MADM are frequently used to profile existing systems to identify positive elements that need to be preserved and poor components that could be improved, thereby guiding the design of new, more sustainable systems [3].

There are many examples of MADM applications for agricultural sustainability assessment. The ECOGEN project [7] focused on assessment of the risk posed by genetically modified (GM) crops to soil quality and function using a qualitative multi-attribute model consisting of 34 attributes hierarchically structured into eight levels. The sustainable agroecosystem model (SAM) [10] integrates an economic model (simulating land use decisions and short-term profit maximisation) with a soils and crop and climate model (simulating yield quality and soil function). However, SAM contains no biodiversity component, so perhaps it could not be considered truly representative of the whole crop system. The multicriteria assessment of the sustainability of cropping systems (MASC) model [11] takes a holistic view of the crop system based on 16 sustainability indicators aggregated into nine types of indices, representing economic, social and environmental dimensions of sustainability and is used to compare four cropping systems. The MASC model was adapted specifically for organic, stockless systems (MASC_OF [3]), but neither example include indicators of biodiversity other than proxy measures based on pesticide inputs. A qualitative multi-attribute model was built using DEXi software [7,8], for holistic assessment of soil quality [12], which does include a biodiversity element, though the above ground components of the system were not included. Finally, DEXiPM was developed to predict system level impacts of adopting IPM strategies [13], to perform post-hoc analysis of IPM cropping systems [14] and was adapted to include a more comprehensive biodiversity component and provide a common framework for sustainability assessment applicable to more than one type of crop system [15].

There are therefore many examples in the literature that use multi-criteria sustainability assessment of cropping systems based on aggregating indicators (see [16] for a review). Most of the earlier published studies tended to focus on either the plot scale or on the wider landscape [17], but more recent research has addressed the need for cropping system-scale analysis, applicable to individual fields where the systems need to be implemented [18]. Cropping system can be defined as a “set of management procedures applied to a given, uniformly treated area, which may be a field or a group of fields” [5,6,19]. MADM assessments of multiple cropping systems at this scale can then be put together to form an overall assessment of a farming system [6]. Here, elements of existing DEXi models [13,15] are extensively developed (DEXi-CSC) specifically to assess the sustainability goals set out at a long-term experimental platform, the Centre for Sustainable Cropping (CSC), Balruddery Farm, Scotland [20–22]. The CSC is based on a whole crop systems framework for designing, implementing and testing an

integrated arable management, which aims to maintain crop yield and quality whilst enhancing biodiversity for system function, reducing environmental pollution due to losses from the system, and improving soil health.

The work presented here describes the overall structure of DEXi-CSC and its component indicators, with the aim of comparing environmental and economic sustainability for winter and spring cereals, potato and field bean, in a six-field rotation under two management treatments. Each system is parameterised from empirical data collected over a duration of six years [22] but here converted to qualitative scores for input variables to the model. Scenarios were run with the aim to test whether the integrated cropping system achieved greater levels of overall sustainability relative to standard commercial practice. This case study demonstrates the value of a ‘whole systems’ approach to compare existing cropping systems and to predict the effect of new systems on arable ecosystem sustainability.

2. Materials and Methods

2.1. Experimental Framework

The CSC long-term platform and indicators are described in detail in [20–22]. Briefly, the platform, which was established in 2009, is based on a framework for designing and testing new cropping systems, in a similar way to the Sustainability Assessment of Farming and the Environment (SAFE) framework [23,24]: First, the overall objectives or end goals of the management system are defined; second, criteria and methods for achieving these goals are determined and third, a suite of indicators representing the key components of the system for monitoring the impact are identified. The high-level objective of the CSC is to maintain crop yields and quality whilst enhancing system sustainability. The methods for achieving this focus on integrating best practice options for managing soil, nutrients and biodiversity [22], summarised as follows:

1. Improving soil structure and biological function through organic matter amendments (42 t ha⁻¹ green waste municipal compost, crop residue incorporation, cover cropping and legume undersowing) [25], non-inversion tillage and tied ridging in potatoes to improve water infiltration and reduce losses [26,27];
2. Enhancing biodiversity through reduced reliance on crop protection chemicals (threshold applications) together with the use of Integrated Pest and Disease Management strategies [28], targeted control of competitive weeds to allow a small understory of dicotyledonous weeds in fields [29] and diverse wildflower mixes sown in field margins to provide resource for beneficial insects [30] and;
3. Reducing environmental pollution by using less mineral fertiliser (*ca.* 70% of the standard rate based on soil nutrient supply) and replacing with nutrients from cover crops and undersown legumes [31,32], increasing efficiency of resource use through field management (1 and 2 above) and crop varieties selected for better resource use efficiency [33,34].

These management options are applied as a single package at the long-term field platform which comprises of six fields over 42 ha in a six-course rotation of potato, winter wheat, winter barley, winter oilseed rape, spring beans and spring barley. Each field is divided into two, allowing direct comparison of the integrated management system on one half against standard commercial practice on the other across all six crops in the rotation [22]. The effect of the integrated management on the whole system is then assessed by monitoring a suite of indicators selected to represent the key environmental (abiotic), ecological (biotic) and economic components of the system [21].

Analysis of data on individual indicators from the first crop rotation indicates that the management strategy achieved many of the overall goals. Crop yields and yield qualities were largely maintained under the integrated system despite an increase in the abundance of dicotyledonous weeds [22,35]. Soil carbon was increased along with the concentrations of the main plant nutrients and pH levels appear to be buffered as a result of compost addition [22]. Soil microbial biomass and carbon turnover

were greater [36,37], litter decomposition rates were faster and earthworm functional group numbers were higher under integrated management (unpublished data). Pollinator numbers were also greater in the diverse field margins and adjacent crops in the integrated treatments (unpublished data). These analyses of individual variates in terms of direct response to treatment and empirical relation to other associated variables are ongoing, but they need to be combined for whole-system sustainability assessment. Here, the suite of agronomic and environmental indicators, along with measures of financial costs were used as the input variables to parameterise the DEXi-CSC model for analysis of whole-system sustainability.

2.2. DEXi-CSC Framework

The DEXi-CSC consisted of 97 input variables that represent the basic biotic, abiotic and financial indicators of the arable cropping system. These input variables were aggregated into a hierarchical tree (summarised in Figure 1 and detailed in full in Supplementary Figure S1) following the method described in [8,13,38], producing 332 aggregated variables in total. Overall sustainability was broken down into environmental and economic sustainability in the second level of the tree. Environmental sustainability was further subdivided into three main branches (biodiversity, resource use and losses) and economic sustainability into two branches (viability and profitability). These branches reflected the main goals of the CSC platform to maintain yield (for the financial viability of farm businesses) whilst enhancing biodiversity (in-field broadleaved weeds and field margins for beneficial invertebrates), increasing the efficiency of resource use (to reduce reliance on non-renewable resources) and minimising losses from the system through leaching, run-off, erosion and greenhouse gas emissions. Note that social sustainability was not explicitly addressed in this framework since comparisons were made at the field rather than farm level, though indicators of social impact could be introduced in the future.

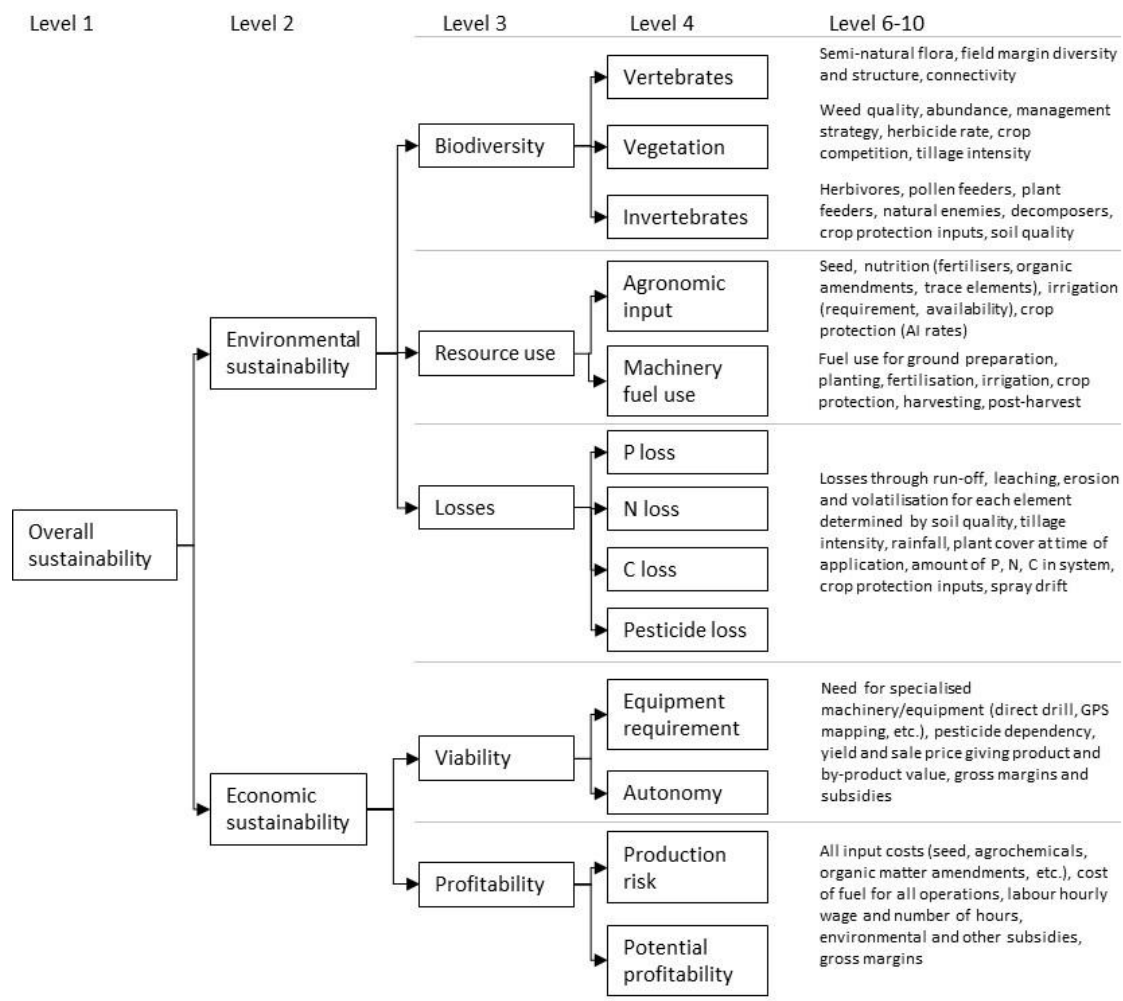


Figure 1. Simplified version of the DEXi-Centre for Sustainable Cropping (CSC) hierarchical tree showing aggregated variables for the top four levels, with a brief description of the main indicators from level 5 and below. See Figure S1 for the full tree.

Each input indicator and aggregated indicator in the tree was associated with a category: Typically, “high”, “medium”, “low”, “none” or for some variables, binary e.g., “yes”/“no”. These categories were assigned a value e.g., high = positive, medium = neutral and low = negative, or vice versa depending on the element in question. Upper and lower bounds for each category were set according to percentiles based on the range of values for each indicator across years and treatments. Elements were then aggregated according to utility functions (if-then rules) and weightings, which determine the influence of the elements at one level on the aggregated element at the next level up in the hierarchy. For example, if an aggregated indicator (A) depends on two indicators (B1, B2) with the qualitative states low, medium and high, and an equal (50:50) weighting on A, then the utility function might be: “if B1 = high and B2 = low, then A = medium”. If the weightings were set to be unequal (e.g., 70:30) so that B1 has a greater influence on A than B2, then the utility function might look more like: “if B1 = high and B2 = low, then A = high”. Altering the weightings in this way allows users to adapt the model for testing alternative scenarios where the priorities for the goals of management or required outputs of the system may be different, so if biodiversity conservation is more of a concern in one case and minimising losses a priority in another, then the same model can be used to predict the impact in both cases with weightings adjusted accordingly. Sensitivity of the DEXi-CSC to changes in the weightings in the top three levels are described in Section 3.2 and weightings for all the elements in the model are given in Supplementary Table S1.

2.3. Case Study Systems for Sustainability Assessment

The DEXi-CSC was parameterised at the cropping systems level, which is the unit at which a management practice was applied to a specific crop. This gave twelve cropping systems to assess: The integrated management system compared to conventional practice for potato, winter wheat, winter barley, winter oilseed rape, spring beans and spring barley. Input variables were assigned to categories based on median values from field data and crop management records collected over the first full crop rotation from 2011 to 2016. Scores for all indicators (inputs and aggregated variables) are given in Supplementary Table S2.

3. Results

3.1. Effect of Cropping System on Sustainability

Overall sustainability scored “high” for all crops and treatments except oilseed rape and potato. This lack of a difference between bean and cereal cropping systems at the top level of the hierarchy masked consistent differences between treatments at lower levels of aggregation. Environmental sustainability scores were high for integrated systems compared to medium or low in conventional systems (Figure 2). Better performance of integrated systems in terms of environmental sustainability was offset by poorer economic sustainability. The reverse was true for conventionally managed crops, resulting in no apparent difference between treatments in terms of overall sustainability. Winter oilseed rape crops showed the same trade-off, but here, a lower environmental score and a higher economic score for conventional management, and the reverse for integrated management, gave a medium overall score for both. The same pattern was found for integrated potato management, but for this crop, the conventional system scored poorly for both environmental and economic sustainability resulting in a very low overall rating.

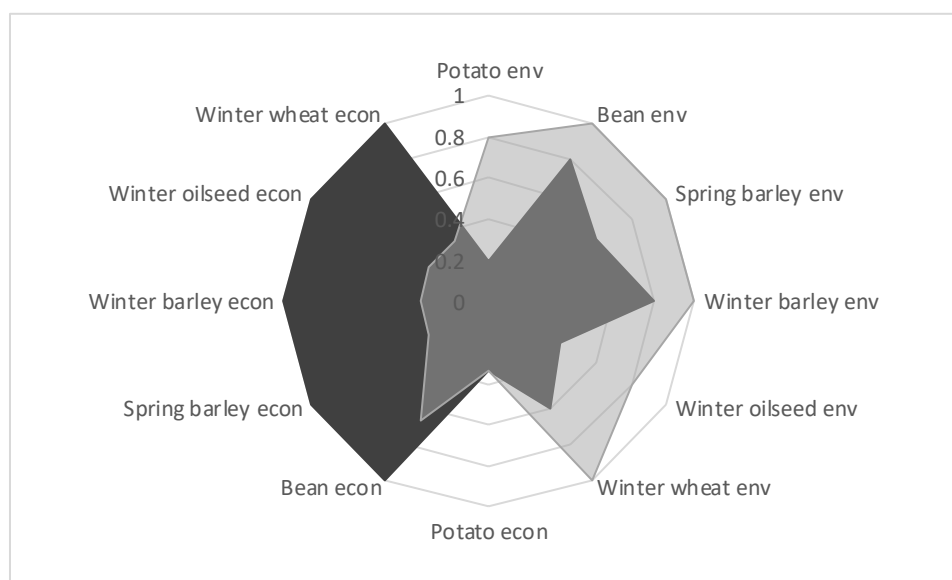


Figure 2. Radar plots of scores for level 2 aggregated indicators: Environmental (env) and economic (econ) sustainability, for each crop in the rotation. Light grey = integrated treatment; dark grey = conventional treatment; intermediate grey = overlap in scores between the two treatments. Scores were graded from 0 = low/negative to 1 = high/positive.

Differences between cropping systems for levels 3 and 4 in the hierarchical tree are shown for each crop in Figure 3. In this figure, high scores (1) represent positive contribution to environmental and economic sustainability (more biodiversity, lower rates of losses, less resource use, greater viability,

autonomy and profitability), and low scores (0) represent a negative contribution to sustainability (low biodiversity, high rates of losses, more resource use, lower viability and profitability).

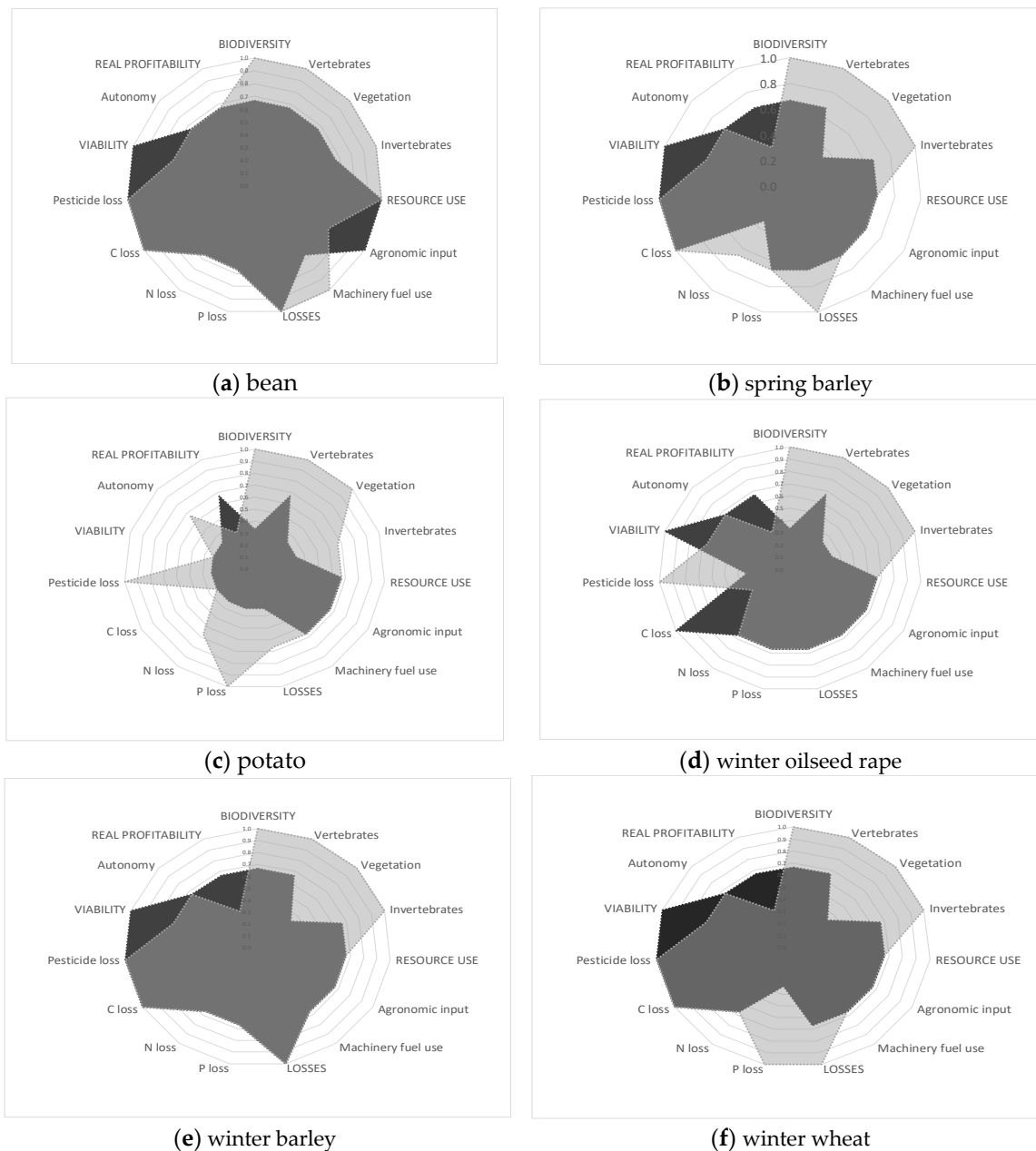


Figure 3. Radar plots of scores for the aggregated indicators at levels 3 (upper case text) and 4 (lower case text) in the DEXi-CSC hierarchy, reading clockwise (e.g., level 3 indicator: Biodiversity, comprises of level 4 indicators: Vertebrates, vegetation and invertebrates). High scores indicate a positive contribution to sustainability, low scores indicate a negative contribution for each indicator. Light grey = integrated treatment; dark grey = conventional treatment; intermediate grey = overlap in scores between the two treatments.

The biodiversity branch, comprising abundance and diversity of vertebrates, invertebrates and plants, scored high under integrated management for all crops due to diverse wildflower field margins and targeted herbicide applications, resulting in a greater proportion of dicotyledonous weeds in fields. This resource for arable foodwebs resulted in higher numbers of herbivores, natural enemies and

pollinators. Finally, better soil quality (less disturbance and more organic matter) resulted in greater numbers of soil organisms including decomposers and invertebrate predators.

The other two branches within environmental sustainability (resource use and losses, see Figure 1) were less consistent across crops. Bean crops scored high for resource use since mineral nitrogen fertiliser is not required, but all other crops and treatments scored medium (Figure 3). This is due to the variation between management treatments in terms of the requirements for agronomic inputs and fuel use. Seed rate, cover crop seed and seed for undersowing were all high in integrated systems relative to standard practice. Fertiliser inputs were low but offset by very high rates of compost inputs used to increase soil organic matter content in the first crop rotation. Agrochemical inputs, on average over the six-year rotation, balanced out across cropping systems as the higher rates of herbicide use, required to deal with specific grass weed issues in non-inversion tillage, offset the reductions in inputs of other crop protection chemicals. Fungicide use was less in integrated than conventional management since applications were based on dose response curves and pest thresholds. Insecticides were used more in conventionally management potatoes and oilseed than the integrated systems but were low for all other crops since insect pests in beans and cereals rarely reach threshold levels in this region. Fuel use was variable across operations with no consistent pattern between cropping systems: Where less fuel may have been used for some operations, e.g., crop protection applications, this benefit was offset by an increase in the number of other operations carried out, e.g., cover crop planting and management. Similarly, integrated cereal systems saved fuel by not baling and removing straw but used more on straw chopping and incorporation.

The ‘losses’ sub-branch of environmental sustainability was also variable across crop systems, being dependent on the combination of: (a) The quantity of each element (plant nutrients, carbon and agrochemicals) present in the system and therefore available to be lost; (b) the demand or requirement of the system for each element (e.g., winter crops, with a high percentage vegetative ground cover over a 12 month period and high yield, accumulate more resources from the system than a field with low cover and low yields) and (c) the field conditions for each of the loss processes (erosion, run-off, leaching, emissions and spray drift), which are highly influenced by soil quality and weather conditions. Losses were low for beans and winter barley and medium for winter oilseed rape, with no difference between integrated and conventional crop systems. Integrated management of potatoes, spring barley and winter wheat resulted in better scores with fewer losses relative to standard practice, primarily due to improved soil quality.

Differences between systems in terms of economic sustainability were driven by poorer performance of the integrated system in terms of viability (for all crops except potatoes where both crop systems scored low) and profitability (for all crops except beans where both systems scored medium). Viability is broken down into autonomy and requirement for agricultural equipment. The latter is an input variable set as low for standard practice, medium for the integrated system (which requires some additional or specialist equipment, e.g., for precision agriculture, cover crop sowing, tied-ridging in potatoes and conservation tillage) and high for planting and harvest operations in both integrated and conventional systems for potato crops. Autonomy is an assessment of the level of independence of the farm in terms of specialization, subsidies, reliance on pesticides and economic efficiency. This is estimated from three main variables:

Proportion of the gross margin due to the main crop—a measure of financial dependence on a single crop type and the spread of risk across crop types in a rotation (specialisation). This was set to medium for all crops/systems in this case study as the crop rotation was the same for both management treatments;

- Pesticide dependency—the value of product (sale price of harvested crop and straw) relative to the amount spent on pesticides to produce that crop. This scored low for all cropping systems except for conventionally managed beans, potato and winter oilseed rape where more pesticide was used per tonne of harvested product than in the integrated treatment;

- Economic independence—the combined effect of direct subsidies supporting economic sustainability (set as none here, but see Section 3.2 for alternative scenarios) and gross margin (the difference between production value (yield and sale price) and production cost (fertilisers, pesticides, fuel, seeds and irrigation)). Economic independence was high for integrated bean crops, conventional winter barley and conventional winter wheat, low for conventional potatoes and medium for all other cropping systems.

Real profitability is a combination of production risk and potential profitability. Production risk in the current model is an input variable designed to capture uncertainty of yield based on climate, risk of pest infestations, etc. This is based on expert judgement for each cropping system scenario and was classified as low for conventional systems where crop protection chemicals were used prophylactically and medium for integrated systems where risk was perceived to be higher due to threshold applications and adoption of integrated pest management strategies (but see Section 3.2). In the future, this will be parameterized according to long-term data on yield variability across systems over multiple rotations, providing an opportunity to incorporate the risk analysis into the model.

Potential profitability is a combination of gross margins, direct subsidies (set to zero for both systems here, but tested in Section 3.2) and labour cost. Labour costs were higher in the integrated system due to a greater number of hours required for additional field operations relative to conventional systems. These inputs resulted in lower profitability scores for the integrated system in all crops (except beans) because the lower cost of agrochemical inputs was not sufficient to offset higher seed and labour costs. Integrated bean crops fared better in terms of gross margins, which balanced the production risk and additional input costs to give an equal score for both systems in terms of profitability.

3.2. Sensitivity Trials

The decision rules that determine the relative influence of each variable on the aggregated indicator at the next level in the hierarchy are assigned according to expert opinion rather than quantitative data. It is therefore important to test the sensitivity of the model to variation in these weightings. A full sensitivity analysis is beyond the scope of this paper, but some trial examples for levels 1 to 3 of the hierarchy are presented here for illustration (Table 1).

At the top level, increasing the weighting of environmental sustainability relative to economic sustainability gave lower scores for overall sustainability in three out of six conventionally managed crops, and higher scores for beans under integrated management. By contrast, shifting the weighting in favour of economic rather than environmental sustainability gave better scores for three conventionally managed crops and worse scores for five out of six crops in the integrated system.

At level 2, a reduction in the influence of biodiversity relative to resource use and losses resulted in better scores for the environmental sustainability of conventionally managed break crops and lower scores for all integrated management systems except beans. Altering the percentage contribution of resource use and losses to environmental sustainability had no consistent effect in conventional systems. By contrast, increased weighting to resource use and decreased weighting to losses had a stronger negative influence on environmental sustainability in integrated systems. Finally, variation in the influence of viability and profitability had no impact on economic sustainability apart from potatoes, where increased weighting to viability produced a better score in both conventional and integrated management systems.

Table 1. Examples of sensitivity trials for decision rules in the top three levels of the DEXi-CSC hierarchy. The effect of changes in % contribution of each branch to the next level up on target scores is highlighted red (negative effect) or green (positive effect). Change is shown relative to the aggregated target variable from the original parameterization of the DEXi-CSC model (bold) for each crop and treatment combination.

Target Branches		Overall Sustainability (Level 1)			Environmental Sustainability (Level 2)					Economic sustainability (Level 2)		
		Environmental: Economic (Level 2)			Biodiversity: Resource Use: Losses (Level 3)					Viability: Profitability (Level 3)		
% contribution of each		50:50	75:25	25:75	40:20:40	33:33:33	60:20:20	20:20:60	20:60:20	50:50	25:75	75:25
Conventional	Bean	High	High	Very High	High	High	High	Very High	Very High	High	High	High
	Potato	Very Low	Very Low	Very Low	Very Low	Low	Very Low	Very Low	Low	Low	Low	Medium
	Spring barley	High	Medium	High	Medium	Medium	Medium	Medium	Medium	High	High	High
	Winter barley	High	High	Very High	High	High	Medium	High	Medium	High	High	High
	Winter oilseed	Medium	Low	High	Low	Low	Low	Medium	Medium	High	High	High
	Winter wheat	High	Medium	High	Medium	Medium	Medium	Medium	Medium	High	High	High
Integrated	Bean	High	Very High	High	Very High	Very High	Very High	Very High	Very High	Medium	Medium	Medium
	Potato	Medium	Medium	Low	High	High	High	Medium	Medium	Low	Low	Medium
	Spring barley	High	High	Medium	Very High	High	Very High	Very High	High	Low	Low	Low
	Winter barley	High	High	Medium	Very High	High	Very High	Very High	High	Low	Low	Low
	Winter oilseed	Medium	Medium	Low	High	High	High	Medium	Medium	Low	Low	Low
	Winter wheat	High	High	Medium	Very High	High	Very High	Very High	High	Low	Low	Low

Input variables to the environmental sustainability branch are based largely on quantitative data, assigned objectively to categories (low, medium and high) based on the median values for each variable collected over multiple years [22]. Similarly, in the economics branch, much of the input data is based on quantitative financial information and tractor time to estimate labour hours. However, there are some input variables to this branch for which there is little or no data currently available and categories were therefore assigned subjectively. These include environmental subsidies (set as medium for all cropping systems) and production risk (set as low for conventional systems and medium for integrated systems). Two alternative scenarios were therefore tested: First, where more subsidies were available for the integrated system (set to high) and less for the conventional system (low), and second where production risk (year to year variation in yield) was less for the integrated system (low) than for conventional management (medium). As would be predicted, both tests resulted in an improvement in economic sustainability scores for integrated systems, and therefore an increase in overall sustainability from medium to high (potatoes and winter oilseed rape) and from high to very high for all other crops.

4. Discussion

Agriculture research has contributed to the rapid intensification of crop production and has helped generate a significant increase in yields during the second half of the 20th century through primarily monodisciplinary studies [39]. Subsequent concerns about the impact of intensification on agroecosystem sustainability have raised the need for an inter-disciplinary approach to understand the functioning of the whole system [40]. Despite an increasing recognition that single issues (crop nutrition or pest control, etc.) are influenced by many other and interrelated factors in the system, very few studies have attempted a truly holistic analysis, incorporating multiple ecosystem services or the functional links between them [41–44].

The case study described here attempted to provide a comprehensive model framework for a whole cropping systems analysis and demonstrated the importance of this approach to enable a full assessment of the costs, benefits and risks of new management practices. At the highest level of aggregation, there were few apparent differences in overall sustainability, yet the integrated cropping system scored higher for biodiversity and many of the environmental indicators than was achieved through standard conventional practice. These benefits were offset by poorer performance in terms of economics, a high-level trade-off frequently quoted as the key challenge for improving the uptake of more sustainable farming practices [41,44].

Environmental and economic indicators differ intrinsically in the degree to which they depend on, and in turn influence, local conditions. The sustainability ranking of most indicators of biodiversity and other environmental attributes are determined by the management of the field over a sequence of crops. The states of soil attributes in particular, but also many biodiversity attributes, are managed within the boundaries of the field. Groups of fields in a landscape may affect habitat for wide ranging organisms, but the quality of habitat still depends on activities at the field scale. Exceptional weather or climatic shifts originating outside the field may have strong effects on indicators in the fields, through prolonged waterlogging or drought for example, but the resilience of soil and other indicators to these external influences still depends on management within the field. Environmental attributes also tend to change slowly, usually over periods of several years or decades. In contrast, the sustainability ranking of economic indicators is determined much more by conditions outside the field. For a crop to be profitable, high yield and quality of produce are necessary, but factors well outside the field will commonly have a determining effect. The cost of inputs, the selling price of outputs, the range of local and export markets can all be volatile and may cause fields to flip between sustainable and unsustainable economic states from one year to the next. In the current example, price and yield variability were not explicitly accounted for as input variables were classified in terms of median values for the period and categorised on this basis. However, variability and risk in a socio-economic analysis of the system is the focus of ongoing research and can be included in the production risk element of the profitability branch in future iterations of the model [45].

There are grounds therefore for judging separately the environmental and economic targets and the various levels of attributes within each. For example, if a cropping system is judged environmentally unsustainable but economically sustainable, then it cannot be sustainable overall. In the longer term, environmentally unsustainable systems will become economically unsustainable as environmental degradation, particularly of the soil, will result in poorer crop growth, increased risk of crop failure and heavier reliance on external inputs. The case study presented here covered just one six year rotation, but longer term trends in the interaction between environmental and economic components of sustainability will be analysed once data from multiple rotations is available. In the meantime, adjusting the weighting among attributes within DEXi is one way to explore possible outcomes from predicted future scenarios. Rather than take overall sustainability as the output, the sustainability ranking of second, third or fourth levels might be more appropriate as a guide so, for example, altering the weightings of the three elements that contribute to environmental sustainability indicated that, in this case study, biodiversity is the main driver of environmental sustainability, and, in integrated systems, losses appear to have a stronger influence than resource use.

Expert opinion is often used to assign weights to the influence of one indicator on the next aggregated variable in the hierarchy. Though subjective, this can be a benefit of these types of models, as personal or political bias in terms of desired output can be explicitly catered for and tested. DEXi MADM is ideal for this purpose because they are transparent models, in which each stage in the procedure is visible and can be modified and the revised assessment made immediately. A MADM is not intended to give a single definitive answer but is designed to assemble and weight data so that the status of a system can be appraised by a group of stakeholders who would wish to assess the contribution of individual indicators to overall sustainability. Thus, a model used by an ecologist to devise conservation priorities and management impacts in agricultural systems may put a higher weighting on the influence of the biodiversity branch to overall sustainability than an agronomic consultant who is likely to put a greater weight on factors influencing gross margin or economic viability. Similarly, policy makers can manipulate input parameters (e.g., environmental subsidies and production risk) to test the likely impact of financial incentive schemes on economic parameters. As demonstrated in this case study, the inherent subjectivity of these weighting factors and the sensitivity of the model output should be recognised where the model is to be used in decision support for managers or to influence policy.

In the comparison of cropping systems here, the integrated management scored lower in economic indicators but higher in environmental sustainability. Trade-offs such as this were evident throughout the hierarchy. For example, benefits of the integrated system in terms of reduced fuel use for spray operations, were off-set (a form of trade-off [43]) by an increase in the number of operations required for sowing and weed control. With the current model parameterization, benefits of the integrated crop system to environmental sustainability were driven by improvements to biodiversity and soil quality rather than the actual amount of resource used. A better assessment of environmental impact through resource use could be achieved by modifying this sub-branch to distinguish between renewable versus non-renewable resources, with greater negative weightings on the latter.

Categorisation of input data (e.g., yield or weed density or chemical application rates) into qualitative, comparative scales is also somewhat subjective and, as with the weighting functions, also has the potential to influence the model results. For example, depending on the level at which the boundary between two categories is set, two very similar values may be assigned into different categories (e.g., low and medium, or medium and high), whereas the actual difference between them may be too small to be commercially or biologically relevant. This has big implications for model results and interpretation. Some sensitivity tests of input variables and the relative weightings between selected attributes have been presented here, but a comprehensive sensitivity analysis will be carried out in advance of its application as a decision support tool to predict the likely costs and benefits of new management strategies on commercial arable farms.

In conclusion, a ‘whole cropping systems’ approach is essential for evaluating outcomes and prioritising management interventions in multi-functional agricultural landscapes and should be accounted for when describing or predicting the effect of new practices on agro-ecosystem sustainability. Studies that focus on single ecosystem services in isolation are likely to result in failure to achieve overall sustainability due to the functional interaction between different components of ecological systems [41]. Sustainability assessment seeks to promote multiple gains, and at the highest level, simultaneous environmental and economic benefits. This calls for more than simply striking a balance between conflicting goals [43]. Negative trade-offs between production and biodiversity can be mitigated through specific management practices e.g., crop diversification to increase yield, biological control to reduce pest pressure and policy interventions (e.g., subsidies), to achieve co-delivery of multiple benefits and “win-win” scenarios [44]. Policy will be particularly effective in achieving more of the latter, since an important environmental benefit that might incur an economic trade-off today can be turned to win-win with appropriate encouragement. For example, supported expansion of grain legumes from their current low base would reduce greenhouse gas emissions, limit pollution to water and benefit biodiversity through creating habitat diversity in-field and in the wider landscape [46].

Although the model framework and case study presented here is designed to encompass key biophysical and economic elements of arable cropping systems, its flexible structure provides opportunities to incorporate social sustainability and life cycle analysis beyond the farm gate. These are important components in scaling up from cropping system to farm and multiple-farm or landscape level sustainability assessments [39,47]. Social sustainability could be included either as a third main branch or else through a social context pervading the existing branches. For example, in the economic branch, attributes such as ‘risk’ and ‘autonomy’, could be made to depend also on the availability of attributes such as workforce, wages, training and safety [48]. Similarly, the current model could be augmented to test the impact at the cropping systems scale of subsidies and international trading relations imposed externally. Future work will therefore include stakeholder participatory development of social, economic and political drivers of sustainability.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4395/9/8/438/s1>, Figure S1: The Centre for Sustainable Cropping whole-systems framework for assessing the sustainability of an integrated cropping system using DEXi-CSC, Table S1: Weightings for each aggregation in the DEXi-CSC, broken down by branch: biodiversity, resource use, losses, profitability and viability, Table S2: Full evaluation of the DEXi-CSC aggregated variables for six crops and two management treatments.

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