REFEREED ARTICLE

DOI: 10.5836/ijam/2013-04-04

Measuring agricultural sustainability at the farm-level: A pragmatic approach

POPPY FRATER[1] and JEREMY FRANKS[2]

ABSTRACT

With increasing political pressure to produce more food whilst being environmentally and socially considerate, alongside the need to cope with climatic extremes and financial instability, farming needs to become more sustainable. To monitor and improve understanding of sustainable agriculture, farmers will need additional tools to illustrate the impacts of their business decisions. However, current tools to monitor the sustainability of agriculture require measurement of variables that are rarely readily available. Moreover these tools exclude farmers in their development and interpretation. This paper suggests a pragmatic approach to creating a farm-based monitoring tool. We propose that farm-level indices of sustainability are initially based only on data that is readily available. Whilst this would increase its appeal to farmers and therefore participation rates, it may initially have little immediate value as a measure of sustainability. Therefore a 'design-action-design' cycle–the basis of adaptive co-management– must be employed to allow the tool to evolve. Starting from this pragmatic, bottom-up perspective, as data collection systems improve, more theoretically driven (i.e. top-down) site-specific variables of sustainability can be included to provide a more comprehensive tool. This paper illustrates the principles involved by (i) calculating a farm-specific composite sustainability index (CSI) for a commercial farm based on readily available data and (ii) emphasising the need to establish better data collection systems.

KEYWORDS: Composite sustainability index; policy; farm-level; pragmatism

1. Introduction: Sustainable agriculture

The concept of sustainable agriculture (SA) has become increasingly influential to agricultural policy (Legg 2006). The term SA is derived from the definition of 'sustainable development' used by The Brundtland Commission (1987): "development that meets the needs of current generations without compromising the ability of future generations to meet their needs and aspirations." Sustainable development focuses on sharing resources spatially and temporally. From this beginning SA has evolved to means many different things to different people (White 2013), so producing an operational definition has proven "extremely problematic" (Rigby and Cáceres (2001). This is not helpful for businesses which require measurable and manageable objectives in order to achieve policy goals and become more sustainable for the benefit of the business.

The range of definitions reflects, in part, our lack of understanding of how ecosystems functions are affected by farming and other anthropogenic interventions in the short- and long-term. However, such definitional flexibility has benefits. A term that remains elusive can be subject to wider interpretation and therefore assume the function of a 'boundary object' (Franks 2010). A boundary object is a concept/idea the meaning of which is 'understood' by everybody ("I know it when I see it" (White 2013)) even though that word's meaning is not necessarily the same for different stakeholders.

The notion of sustainability as a boundary object has two important implications for agriculture. Firstly, it becomes necessary for all stakeholders to jointly develop an agreed and more complete, site-specific understanding of the impacts of farming on key ecosystem services. Secondly, approaches which claim to deliver SA must be constantly monitored, evaluated and reassessed over time. These dual requirements have increasingly led conservationists to include all sources of knowledge in their efforts to develop a more complete, locally-based understanding of farming's environmental impacts (e.g. life cycle assessment (Cederberg and Mattsson 2000)). This trend towards closer collaboration between researchers, policy makers and practitioners has developed a community of interest focused on *sustainable science* (SS) rather than *sustainable development* (Kates *et al.* 2005). It has also led to the development of notions of active and passive adaptive co-management (Armitage *et al.* 2008).

Active and passive co-management both recognise that rights and responsibilities should be shared among those with a claim to environmental and natural resources (Plummer 2009). In their discussion of the differences between active and passive co-management, Rist *et al.* (2013) make it clear that both incorporate the

Original submitted July 2012; revision received March 2013; accepted April 2013.

[1] EBLEX, Agriculture and Horticulture Development Board (AHDB), Stoneleigh Park, Kenilworth, CV8 2TL. Poppy.frater@eblex.ahdb.org.uk

[2] School of Agriculture, Food and Rural Development, Agriculture Building, Newcastle University, Newcastle upon Tyne, Tyne and Wear, NE1 7RU. J.R.Franks@ncl.ac.uk

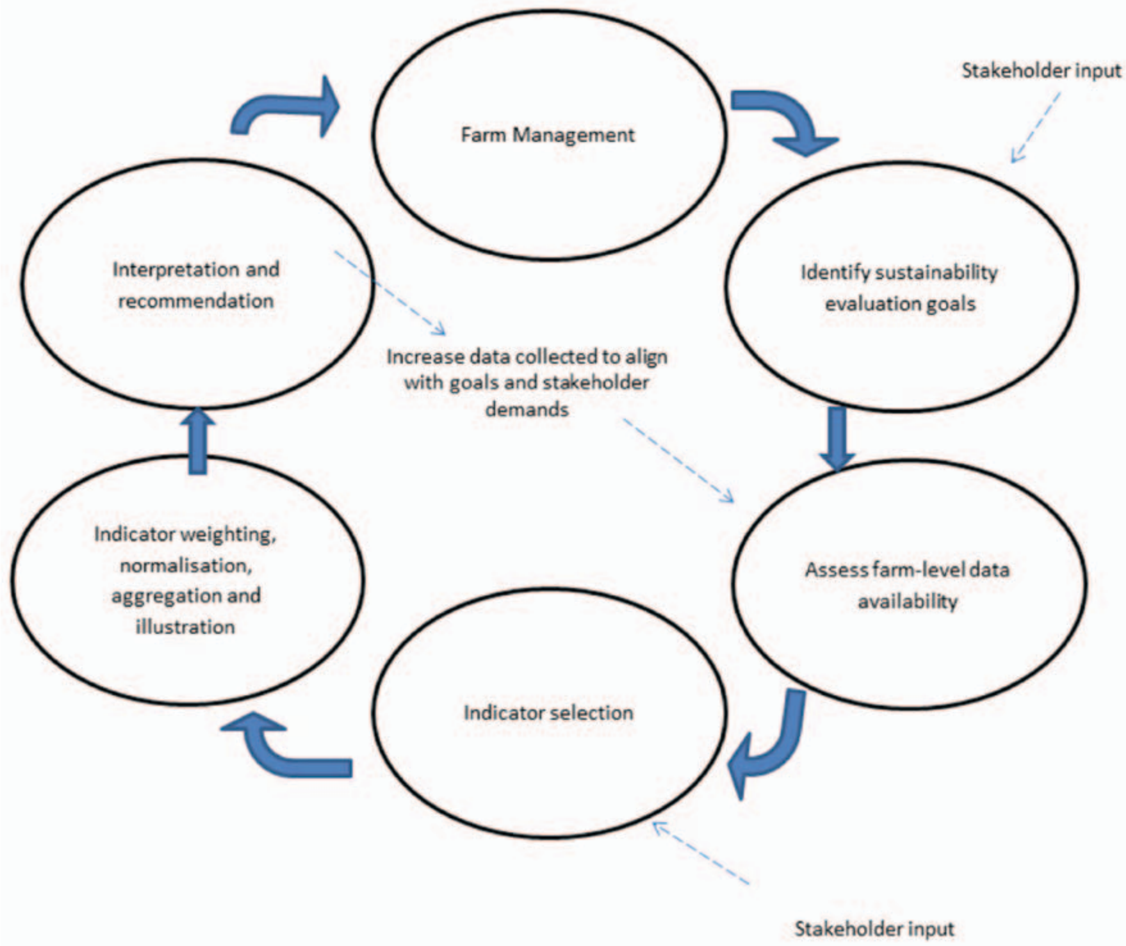

Figure 1: The concept of 'design-action-design' cycle in the evaluation of sustainable agriculture

need to modify activities as knowledge and experience grows. Both approaches incorporate the 'design-action-design' cycle. Adaptive co-management does so within a more deliberate experimental framework, while passive co-management is based upon a single course of action formulated using best available modelling and evidence (Rist *et al.* 2013). In this way, learning through experimentation (within a formalised framework, with informed and interested parties) can become instrumental in driving forward our limited understanding of agricultural sustainability.

Design-action-design

A 'design-action-design' approach to applying a specific sustainability measurement tool- the composite sustainability index (CSI)[2]- to quantify all aspects of SA is outlined in Figure 1. Indicators are based on measurements in order to record trends in relation to pre-specified policy objectives and targets. As the methodology develops, redundant measurements and new measurement requirements are identified.

As understanding of the environmental impacts of farm management decisions become clearer, management blueprints need to be revised and thereby the sustainability of individual farm businesses can improve. This is particularly important because whether a practice is sustainable depends upon the context within which the techniques and practices are used; what represents a sustainable technique will "vary both temporally and spatially" (Rigby and Cáceres 2001).

We argue for a bottom-up perspective to determine indicator selection rather than the top-down perspective because, despite a degree of uncertainty, action is required to evaluate SA (Rigby and Cáceres 2001) and we believe a pragmatic approach is the best way to move forward. Our starting definition of SA will be taken from the Sustainable Agriculture Initiative as the 'need to safeguard agricultural products, while protecting and improving the natural environment and social/economic conditions of local communities' (SAI 2010). Many variables might be used to reflect each component of the triple bottom line (a point that is discussed later), but the pragmatic approach would be limited by variables that are currently readily available. In this way, widespread participation is more likely because application is non-prescriptive. Individual farms are likely to have different data readily available therefore the initial index will vary across farms, with a degree of convergence developed over time to encompass information summarising the triple bottom line.

Over time the index will develop to more accurately reflect local sustainability targets as indicated by local environmental targets (e.g. Natural England's natural

[2] The CSI aggregates multiple indicators to provide a single value and/or a diagrammatical representation of the sustainability of a process. An indicator is a qualitative or quantitative measure that reflects a criterion and can be used as a standard on which a judgement or decision may be based (López-ridaura *et al.* (2005)).

character area priority concerns), economic requirements to maintain a thriving and successful business, and the resources demanded and supplied by the rural economy. Convergence will allow the indicator to be compared on a like-for-like basis between farms. Over time therefore, the variables measured and combined into a single sustainability index value will more closely reflect the farm's short- and long-term resilience and the ecosystem's ability to buffer shocks (Pretty 2008; Darnhofer *et al.* 2010). The initial pragmatically identified starting-point will quickly develop to use variables more closely aligned with the theoretically developed notions of sustainability.

The next section puts this approach into context by reviewing the literature to identify competing methods to assess farm-level sustainability. This is followed by a review of how the CSI is typically constructed and suggested methods to develop a farm-level CSI. Section 4 illustrates application of the CSI on a commercial farm. Section 5 discusses the benefits and disadvantages of the pragmatic, bottom-up approach compared to the theoretically driven, top-down approach. Section 6 concludes.

2. Methods to assess agricultural sustainability

The literature review suggests current agricultural sustainability tools are based on adapted versions of four main methods: life cycle analysis (LCA), green accounting, ecological footprinting and the CSI (Table 1). Whilst LCA is comprehensive (Cederberg and Mattsson 2000), it is also expertise- and time-intensive, which limits its applicability. It also doesn't typically include economic and social measures and struggles with qualitative data (e.g. biodiversity) (Lindeijer 2000). Green accounting incorporates the economic pillar of sustainability (Bartelmus 1999; Bartelmus and Vesper 2000; Halberg *et al.* 2005), but is also difficult to apply due to large data requirements and methodological fallibilities, particularly related to the estimation of monetary values for non-marketed public goods and other ecosystem services. It is generally not applied at the farm-level. Ecological footprinting developed by Wackernagel and Rees (1996) adopts a more pragmatic approach. Calculating the area of land used is relatively straightforward, and farm greenhouse gas (GHG) emissions and carbon sequestration can be estimated using LCA and on-line calculators (such as the Carbon Accounting for Land Managers calculator (CLA 2009) or the Cool Farm Tool (Cool Farm Institute (2012)). However, Ecological footprinting only assesses a portion of the environmental dimension of sustainability (i.e. land-use, GHG emissions and chemical outputs). On the other hand, it could form part of the holistic assessment.

Each approach has its advantages and shortcomings and each has been widely used. However, as it is generally considered necessary in sustainability evaluation to embrace all three dimensions and scales of rural land management- the assessment method needs to be multi-dimensional and the CSI approach is the only one with the capacity to achieve this.

The ideal CSI uses a straightforward, flexible and repeatable methodology to allow meaningful intra- and inter-farm comparisons (e.g. Nambiar *et al.* (2001), Rigby *et al.* (2001), Gómez-Limón and Riesgo (2009)). Like other approaches, the CSI can condense sustainability into a single data value which provides an efficient and easy to understand summary of status and trajectory towards targets for external stakeholders. The main drawback of the CSI approach is the difficulty practitioners have in agreeing: (i) which variables to use in the composite index and (ii) how to combine these variables in a way that best reflect each variable's contributions to sustainability. Nevertheless, it is because the benefits outweigh the disadvantages that studies have used the CSI methodology to measure sustainability across a large number of industries (e.g. steel OECD (2008)) and scales (e.g. village catchment, e.g. Izac and Swift (1994) to country, e.g. Bandura (2008), Esty *et al.* (2005)).

3. Composite Sustainability Index (CSI): methodological issues

A CSI is created from numerous component variables which are amalgamated to provide a summary of sustainability in a single value and/or informative radar web (sustainability web) (e.g. AMOEBA[3] (Wossink 1995)) . The variables that are typically selected reflect the researchers' notion of sustainability. To create a CSI, five methodological issues need to be addressed sequentially (Gómez-Limón and Riesgo 2009):

(i) Selection of the all the variables to be used in the CSI;
(ii) normalisation of each of these variables;
(iii) assigning weights to each variable which reflect that variable's contribution to that particular dimension of sustainability;
(iv) aggregation of these normalised values to create the mulit-dimensional CSI;
(v) presentation of the CSI so it can be easily and accurately interpreted.

This section illustrates the different approaches practitioners have used at each of these steps.

Selection of the component variables of sustainability

When selecting which variables to use, practitioners have typically started by defining sustainability and then traded the ease of obtaining data with the theoretical importance of the variable in their definition. One direct consequence is that studies have used a wide range of variables in their model (Table 2). Whilst this suggests that CSIs are highly subjective, environments and the threats to them do vary, so indicators do need to be country-, regional- and farm-specific. They will also depend on the development stage of the region and the intended use of the CSI (QIU Hua-jiao *et al.* 2005).

A study of Table 2 shows that selected variables tend to fall into one of two categories. They are either directly measured or ranked in relation to one another (e.g. those based on different management practices) (Nambiar *et al.*

[3] AMEOBA is a Dutch acronym translating to 'general method of ecosystem description and assessment'. The method depicts the sustainability of the business as a 'map' reflecting attainment of selected attributes.

Table 1: Details of a selection of agricultural sustainability assessment methods

Assessment tool	Principles	Merits	Drawbacks	Data requirements	Literature examples
Life Cycle Analysis (LCA)	Detailed examination of the environmental burdens arising from production.	Comprehensive account of a product's environmental impacts.	Rigid system boundaries make accounting for changes in the system difficult. Lacks social dimension. Requires time and expert input to apply.	Inventory of all flows from and to nature, (e.g. energy and raw material inputs) and their impact assessment.	Cederberg *et al.* (2000), Williams *et al.* (2006)
Green accounting (GA)	Extension of the conventional economic accounts to include natural resource use and abuse by economic activity (Bartelmus *et al.* 2003).	Provides incentives to improve the way we use natural resources.	Commodifies nature. Valuation must be continually updated. Difficult to apply money-metric measures of value.	Key ecosystem services, their physical parameters and means of valuation.	Grêt-Regamey and Kytzia (2007)
Ecological Footprinting	'area of productive land and water ecosystems required to produce the resources that the population [under assessment] consumes and assimilate the wastes that the population produces (Rees 2000).	Condenses complex impacts into a single intuitive number.	Fails to account for greenhouse gas emissions, national boundaries, intensive production and land degradation over time.	Land area occupied, farm emissions, land area used to produce the inputs produced off-farm (e.g. non-renewable energy, feed).	Van der Werf *et al.* (2007)
Composite Sustainability Index (CSI)	Aggregation of a combination of multidimensional indicators to formulate a composite indicator.	Summarises multiple measurements for ease of interpretation and comparison. Flexible approach	Indicator choice and weightings method are subjective. May conceal problems in the farm production process.	A range of measurements based on the set of indicators selected.	Rigby *et al.* (2001)

Table 2: Details of the methods used in ten research papers applying sustainability indicators at the farm-level

Authors	Country	Products	Sustainability dimension	Indicators selected	Aggregation and Interpretation	Output form
Castoldi and Bechini (2010)	Italy	Cereals and forages	Economic Environment	Variable costs Gross Income Gross Margin Nitrogen soil surface balance Phosphorous soil surface balance Energy Input Energy Output Energy Gain Load index algae Load index crustaceans Load index fish Load index rats Crop sequence indicator Soil cover index Soil organic carbon indicator	Summed stakeholder rank for each system are averaged for easy comparison	Global Sustainability Index
Gómez-Limón and Riesgo (2009)	Spain	Winter cereals Spring crops (maize, sugar-beet, Sunflowers, potatoes, etc.)	Economic Social Environmental	Income of agricultural produce Contribution of agriculture to GDP Insured area Agricultural employment Stability of workforce Risk of abandonment of agricultural activity Economic dependence of agricultural activity Specialisation Phosphorous balance Pesticide risk Use of irrigation water Energy balance Agro-environmental subsidy areas Mean area per plot Soil cover Nitrogen balance	Used a joint analysis with different techniques of aggregation and weighting methods. Aggregation methods compared were: weighted sum of indicators, product of weighted indicators, and a multicriterion function to represent total, partial and varying degrees of compensation. Weighting methods included statistical and expert-input methods	Composite Indicator of Agricultural Sustainability (CIAS) comparing rain-fed agriculture and irrigated agriculture
Williams et al. (2006)	UK	Bread wheat, potatoes, oilseed rape, tomatoes, beef, pig meat, sheep meat, poultry meat, milk, eggs	Environment	Primary energy used GWP Eutrophication potential Acidification potential Pesticides used Abiotic resource use Land use Irrigation water	Comparisons of ten commodities per tonne of product allows the reader to see which commodities are more efficient with respect to the indicators and yield (i.e. data is not aggregated into a single index)	Data in raw form per tonne of product and per hectare

Table 2 continued: Details of the methods used in ten research papers applying sustainability indicators at the farm-level

Authors	Country	Products	Sustainability dimension	Indicators selected	Aggregation and Interpretation	Output form
Pimentel et al. (2005)	USA	Corn, soybeans, corn silage, wheat, alfalfa hay, winter wheat	Environment Economic	Crop yields (Under normal rainfall and drought) Energy inputs Soil Nitrogen Nitrate leaching Herbicide leaching Soil biology Soil carbon Net return	No aggregation, highlights the significant differences found and proposes that organic farming is more sustainable	Indicator comparisons per hectare or percentages for the three systems in the study
Pacini *et al.* (2003)	Italy	Cereals, broadbeans sugar beet, milk, beef	Environment Economic	Nitrogen leaching Nitrogen run-off Nitrogen losses Phosphorous sediment Soil erosion Environmental potential risk indicator for pesticides Herbaceous plant biodiversity indicator Arboreous plant biodiversity indicator Hedge biodiversity indicator Crop diversity indicator Revenues Variable Costs Gross margin	No aggregation, yet the paper compares compliance of farms with environmental thresholds from literature and laws and regulations	Comparison tables between organic, integrated and conventional farms, data in raw form given per hectare or % area
Reganold *et al.*(2001)	USA	Apples	Environment Economic Social	Soil quality Adverse impacts of pesticides and fruit thinners Energy input: Output ratio Orchard profitability Fruit yields Size and grade Tree growth. Leaf and fruit mineral content Fruit maturity Consumer taste tests	No aggregation but inference of sustainability based on incorporation of external costs and valuation of ecosystem services	Comparative tables of soil quality, yield, environmental impact, economics and energy balances of the three systems
Rigby *et al.* (2001)	UK	Various	Environment	Seed source Soil fertility Weed control Pest/disease control Crop management	Weighted sum of scores. Wide ranging results show that other factors are involved in the determination of sustainability	Web diagrams comparing organic and conventional horticultural systems

Table 2 continued: Details of the methods used in ten research papers applying sustainability indicators at the farm-level

Authors	Country	Products	Sustainability dimension	Indicators selected	Aggregation and Interpretation	Output form
Nambiar *et al.* (2001)	China	Various	Environment	Agricultural nutrient balance Crop yield Fertiliser use efficiency/ Irrigated water use efficiency (%) Soil erosion *t*(soil/km2)/ soil saline content Input/output of energy Clay content (%) Soil depth (cm) Bulk density Available water capacity Organic matter Phosphorous soil surface balance Permeability Electrical conductivity Cation Exchange Capacity (CEC)	Weighted product of all sustainability components. Annual means for each region are calculated and compared	Agricultural Sustainability Index
			Economic	Income per labour Real net output per land unit		
			Social	Cultural level		
Haas *et al.* (2001)	Germany	Dairy	Environment	Application of herbicide and antibiotics Potential of nitrate leaching NH_3-emission Grassland (no. of species, date of first cut) Hedges and field margins (density, diversity, state/care, fences) Grazing animals (period, breed, alpine cattle keeping) Layout of farmstead (regional type, buildings, farm garden, trees, orchard)	Used estimated thresholds to normalise the data to graph using radar charts, therefore no single CSI is produced and systems are compared based on the ‘space’ they occupy in the graph	Inventory (schematic) of selected impact categories and indicators of Life cycle assessment for 3 system types
			Social	Housing system and conditions, herd management (e.g. Lightness, spacing, grazing season, care)		
Jansen *et al.* (1995)	Costa Rica	Various	Environment	Balances of N, P and K in soil	Linear programming model to aid achievement of sustainable land use at higher levels	GIS mapping of biocide index and nutrient balances for the four system types

2001). Directly measured variables require greater time and resources, whereas ranked measurements can add to the subjectivity of the study. However, ranked measures do allow positive and negative scoring reflecting the potential positive and negative impact of management activities (Rigby *et al.* 2001). Though selection of variables is typically guided by theory, additional subjectivity occurs in selecting the variables to use in the final index as those which reflect the same aspects of sustainability will need to be whittled down to prevent multicolinearity (overlap).

To help address these problems, a participatory approach which employs stakeholders expertise is recommended (Hodge and Hardi 1997; Speelman *et al.* 2007). For example, López-ridaura *et al.* (2005) obtained stakeholders' views through two rounds of interviews and selected from amongst the views offered using a hierarchical decision-making process. After identifying the objectives of the stakeholders, suggested variables were classified into one of the following sustainability attributes: productivity, stability, reliability, resilience or adaptability (López-ridaura *et al.* 2005). The second round of stakeholder interviews used these sustainability attributes to select the variables to use in the CSI and to estimate the weights to attach to each composite variable. Finally the selected indicators and their values were considered by their spatial scale (i.e. farm-level, regional, national or global) (López-ridaura *et al.* 2005). For this method to be acceptable it must include representatives across the entire stakeholder spectrum; a balanced and carefully selected interviewee group is necessary. Some studies use a hierarchical method to determine dimensions of sustainability and refine the indicator set so it meets the goals of the study (e.g. Hani *et al.* (2003), Zahm *et al.* (2006)). Other studies employ expert panels to select variables considered to be analytically sound, measurable and of policy relevance (e.g. Gómez-Limón and Riesgo (2009)). Alternatively, one can select component variables for a CSI by reference to the literature (Castoldi and Bechini 2010). Table 3 displays the large number of attributes of sustainability captured in a selection of published studies, which could inform the indicator selection process.

Normalisation

Once variables have been selected they need to be transformed onto a common scale in a process termed normalisation (Gómez-Limón and Riesgo 2009). This allows each to be compared with the others. Several approaches have been used to normalise variables (see OECD (2008) for a comprehensive account). The following have been applied at a farm-level:

(1) Use of site-specific tolerability ranges or reference values to scale variables (Eckert *et al.* 2000; Gómez-Limón and Riesgo 2009) these values can be hard to obtain unless their availability had formed the basis for variable selection.

(2) The min-max approach (OECD 2008; Gómez-Limón and Riesgo 2009), this is the observed value for the specific variable minus the minimum value in the data set for that variable divided by the range in the data set for that variable (OECD 2008). For example, if a selected variable has a value of 200, and the range and minimum values found in the dataset for that variable are 250 and 50 respectively, then the observation's min-max normalised value would be calculated as (200-50)/250 and equal 0.6. This is only useful to compare amongst those in the sample.

(3) In their comparison of different farm systems Maeder *et al.* (2002) took the values of the selected variables from one system as the reference values and used this to compare with the variables' values recorded in the other systems. This approach can be used when working with a small sample and when variables need to be interpreted relative to one another. It may be most useful when values need to compare change over time rather than between locations.

Weighting of the indicator values

Generally weights are assigned to each selected variable according to the contribution that variable makes to agricultural sustainability (OECD 2008). Again, stakeholder consultation can assist at this stage. For example, Castoldi and Bechini (2010) asked a sample of farmers, researchers, agronomists, decision-makers and environmentalists to assign weights to selected variables to reflect their views of the contribution each variable made to agricultural sustainability. Each agricultural system was ranked by applying the weights provided by these expert groups (Castoldi and Bechini 2010). A less involved method uses weights reported by a single expert panel (Zahm *et al.* 2006; Gómez-Limón and Riesgo 2009).

Other studies score the sustainability of different agricultural practices using their knowledge of sustainability-impacts and the scientific literature (e.g. Rigby *et al.* (2001) and Rodrigues *et al.* (2010)). For example, using the literature as a base for identify commonly used criteria of agricultural sustainability, Rigby et al. (2001) allocated a score to a range of farming practice based on whether that practice was considered to improve or diminish a farm's environmental impacts. Although open to criticism because of the added subjectivity, this approach facilitates the widespread application of sustainability indices. Moreover, if clear links between action and environmental impact can be identified, these links can be standardised even though they are estimated by different researchers.

Aggregation

The method chosen to aggregate normalised and weighted variables influences the 'compensation' permitted between them, i.e. it influences the degree to which favourable practices are allowed to offset harmful ones (Bockstaller *et al.* 1997). The method of 'summing of scores'[4] allows full compensation between the component variables, which may be sensible where variables are related. For example, a low level of animal diversity can be partially compensated by a higher degree of crop diversity (Zahm *et al.* 2006). However, full compensation is not appropriate for all indicators; a low level of nitrate leaching cannot balance a higher level of pesticide volatization (Bockstaller *et al.* 1997). Compensation between measures can be limited by assigning high weights to one (e.g. nitrate

[4] Summing of scores is where the value for each variable is summed to produce an aggregate value. This method allows some values to offset others as full compensation between values is permitted.

Table 3: Attributes used in the literature to assess farm-level sustainability

Attributes	Jansen *et al.* (1995)	Eckert *et al.* (2000)	Haas *et al.* (2001)	Nambiar *et al.* (2001)	Reganold *et al.* (2001)	Rigby *et al.* (2001)	Hani *et al.* (2003)	Pacini *et al.* (2003)	Pimentel *et al.* (2005)	Zahm *et al.* (2006)	Gómez-Limón and Riesgo (2009)	Castoldi and Bechini (2010)	Rodrigues *et al.* (2010)
Ecological integrity	X	X	X	X	X	X	X	X	X	X	X	X	X
Economic viability					X	X	X	X	X	X	X	X	
Energy efficiency		X	X	X			X		X		X	X	
Productivity	X	X		X	X	X			X				
Social Integrity				X		X	X			X	X		X
Diversity		X						X				X	X
Health and welfare			X							X		X	X
Landscape image			X							X			X
Produce quality					X					X			
Subsidy independence								X			X		
Reproducibility		X								X			
Longevity											X		
Risk aversion													X
Self sufficiency						X							
System efficiency		X											

leaching) and low weights to the other (e.g. pesticide volatization) relative to the importance placed on each variable. The literature uses three approaches to aggregate selected variables into a single CSI value:

(1) weighted product (e.g. Nambiar *et al.* (2001));

(2) weighted sum of score (e.g. Zahm *et al.* (2006));

(3) use of a computer algorithm, such as Principal Component Analysis (PCA), (e.g. Sands and Podmore (2000)).

Nambiar *et al.* (2001) summed the normalised variables and then multiplied these composite indicators together to form an Agricultural Sustainability Index (ASI). This approach allows the related variables in each composite indicator to fully compensate each other, whilst the multiplication allows partial compensation between the composite indicators (Gomez-Limon and Riesgo, 2009). PCA has also been used, but as this requires a large number of observations it cannot be used to assess the sustainability of small samples (Sands and Podmore 2000; Barrios and Komoto 2006).

Some researchers by-pass the aggregation stage, or add to the aggregate value, by using diagrams, such as sustainability webs, in which relative value of each variable/component indicator is illustrated without aggregation (Haas *et al.* 2001; Rigby *et al.* 2001; Hani *et al.* 2003; Speelman *et al.* 2007). This approach normalises each variable/component indicator to a value between zero (the centre of the web) and 1 (the edge of the web) with each variable/component indicators value assigned to its own 'spine'. This allows users to see clearly which attributes of sustainability have a strong and weak presence in the study. This transparency can complement the presentation of a single, summary CSI value as it allows users to assign to the data weights which more closely suit their own purposes and understanding.

Indicator relationships

Individual component indicators used to calculate a CSI are likely to influence each other (Speelman *et al.* 2007). For example, Speelman *et al.* (2006) analysed the trade-off between the retention of crop residue to reduce soil erosion and soil loss in a region prone to soil loss in Mexico. They conclude that 100% crop residue retention would negatively affect farmer's incomes, but 35% crop residue retention combined with free grazing, maximised net income, improved forage self-sufficiency and reduced soil loss. This implies that there are circumstances when the allocated weights need to be non-linear, that the influence of one variable on another must be permitted. However, this generally requires detailed knowledge of many interactions, information that is often simply not available. In these cases, evaluations may benefit from using reference values/regulatory targets (see for example Eckert *et al.* (2000), Gómez-Limón & Riesgo (2009)) using the approach which allows comparisons against a 'norm' or a 'tolerable range'. Additionally, researchers and stakeholders should consider the interactions between indicators at the weighting stage.

Section summary

This section has referred to many studies which have addressed the problems relating to summarising multi-variable conditions in a single value. In view of the wide range of definitions and dimensions assigned to sustainability, it is perhaps not surprising that there is no accepted agreement on the use of a restricted set of variables, agreement on the weights to assign to each variable and to the aggregation step. As a consequence CSIs are not used as yard-sticks in policy instruments despite their potential for comparing trends in sustainable resource use and sustainability over time, between locations and systems.

This study addresses these problems from a farmer-centred perspective. It is based on the assumption that CSIs are able to measure sustainability *over time at the same location*. It also takes into account the practical reality that such measures are more likely to be calculated if they can be implemented at little cost. To facilitate this, it is argued that CSI must be developed by utilising readily available information, but that variable selection will evolve through time using 'design-action-design' cycles. For example, data on important variables, such as percentage of inputs sourced locally may not exist in the initial years, and annual changes in selected variables will not exist in the first year of the study. New data recording systems would need to be established to measure variables for which data is not currently available. This may be relatively inexpensive to do, especially if examples of best-practice recording are exchanged between farmers.

4. Application of farmer-centred CSI: a conventional dairy system

An example of the calculation of a farmer-centred CSI using readily available data in the first stage in a 'design-action design' cycle used data gathered from the Newcastle University owned, 300ha tenant farm located 12 miles west of Newcastle upon Tyne near Stocksfield in the Tyne valley (OS grid reference NZ 064 657). The farm is at an average elevation of 112m, benefits from well-drained sandy clay loam soil and has an average rainfall is 630 mm/yr (MetOffice 2011). The principal enterprises are dairy and arable, though it has a small-scale vegetable enterprise and produces beef. The farm is unique in the UK in that a block of 135 ha is managed organically with the remainder farmed conventionally[5].

Step one requires the selection of variables to use in the CSI. An initial list of 43 indicators was drawn up based on those used in the literature listed in Table 2 (see Appendix 1). Each represents at least one of the three pillars of sustainability and taken together they embrace the majority of the sustainability attributes listed in Table 3. It is noted that the environmental pillar appears to be over-represented compared to the social pillar.

To prevent overlapping between variables, make the CSI more tractable and to reduce costs this list was whittled down in discussion with the farm manger, based on three criteria: (i) ease of availability of data; (ii) accuracy of measurement and (iii) coverage of all dimensions of sustainability. Farm data over a five year period (2005- 2010) was recovered from two computer

[5] The study calculated a CSI for the organic and conventionally farmed land, but only those values computed for the conventionally managed farmland are presented here.

Table 4: Selected variables for current study with definitions

Component Indicator	Units	Definition
1. Nitrogen (N), phosphorous (P) and potassium (K) balances	Kg /ha	The difference between N/P/K input and crop N/P/K requirements (calculated from cropping history, soil texture, target market, etc. using the UK Fertiliser Manual (Defra 2010))
2. Profit margins	£/ha	Income minus fixed and variable costs per hectare
3. Subsidy dependence	%	Percentage of income derived from subsidies (i.e. Single Payment Scheme payment and Entry Level Stewardship payments)
4. Productivity	t/ha	Grain sold off farm, excluding forage crops used on-farm
5. Diversity		
6. Field size	Ha	Average field size
7. Crop diversity	Index (H_s)	Shannon Weaver diversity Index based on the number of crop types and their respective proportions

programmes: Farmplan Computer System (part of Reed Business Information ©) Crop Manager and Farm Business Manager.

Ready availability of data is the prerequisite for this study which takes as its starting-point the farmer's perspective, though the fact that the farm was divided into organic and conventional production systems created data availability problems that might not be encountered on typical farms. Eventually six variables were selected, one of which (diversity) being a composite made up of two measures (Table 4).

The principles of easy access to accurate data and adaptability to local conditions means that the variables selected for another farm would most likely vary from this list (in content and number) at the first rounds of the 'design-action- design' cycle. This should not be seen as a problem given the intention to evolve the selection over time so more variables are available from which indicators can be selected.

The min-max method was used to normalise the selected variables (OECD 2008; Gómez-Limón and Riesgo 2009). Each variable will have a different optimum value, for example, the optimum nitrogen (N), phosphorous (P), potassium (K) balance is assigned the value of zero which represents ecological integrity, economic viability (i.e. the fertilisers are being used at optimum efficiency), and minimal health and welfare risk in terms of nutrient leaching (Table 5). To ensure high values signified positive effects on sustainability, indicators of poor sustainability, such as high subsidy dependence and high nutrient surpluses/deficits were inverted. The maximum and minimum values were derived from pooling variable values over the 5 year period, and the minimum value for each variable subtracted from its observed annual value which was then divided by the range of that variable within the 5-year period. In this way the normalised values reflect the variance within the system over five years, annual min and max values can be used on larger data sets.

To calculate the weights to assign to each variable, each indicator was scored against the number of attributes of sustainability it encompasses (in Table 5). The recorded value of each variable was therefore multiplied by this weight and the products summed into a single CSI. This approach was compared to using an unweighted CSI to investigate the significance of weighting. Unweighted CSIs were calculated by multiplying the normalised value of each variable by 0.17 (i.e. as there are six variables each is given a weight of one sixth), and summed for each year. These normalised variables are then presented in 'sustainability webs' (produced using Microsoft Excel 2010 © radar charts).

5. Research findings

The weighted and un-weighted CSI for each year is listed in Table 6. Both approaches show that the farm was most sustainable in 2007 and least sustainable in 2005. No clear trends can be deducted from either CSI (Figure 2) which infers that no progression or regression is occurring. Year 2005 and 2007 appear out of line with the sample average. The farm manager would most likely be able to identify the reason for this, but it may be caused by factors external to the farm and as such be beyond the managers control (such as input and output prices, weather and staff health).

The sustainability webs for each of the five years showing the underlying value of the selected variables is presented in Figure 3 – confirming the lowest value occurred in 2005 and the highest in 2007. Profit margin was highest in 2005 when subsidy dependency, crop variety diversity and field area were lowest, in terms of sustainability. Conversely, profit margin reduced in 2007 when these same variables and yields were highest. This suggests there may be a trade-off between profit margin and the other indicators. As mentioned above, the variable/composite indicator used to calculate the CSI value ideally needs to measure a different aspect of sustainability to keep overlap (i.e. correlation) to a minimum, but those in the example are closely related hence the notable trade-offs occurring. With the nature of agriculture, one could argue that a multitude of factors do interlink, thereby making the selection of unrelated factors difficult.

The results suggest that (i) the selected weights had little discernible impact on the CSI value and (ii) the variables selected are closely correlated with the year with no clear trend prevailing. This reinforces the need to develop this on-farm CSI within the 'design-action-design cycle' framework. To facilitate this it is important to develop tools that can assist farmers to measure and record a wider selection of variables each year. If these data were pooled across a larger sample of neighbouring farms they could be normalised using the min-max of the sample rather than from the same farm. Widening the sample across which variables are measured would also allow the CSI to be more use as a benchmarking

Table 5: Scoring of the selected indicators based on attributes from the literature

Measure	Sustainability attribute													Score	Overall weighting (score/ total score)
	Ecological integrity	Economic viability	Efficiency	Productivity	Social integrity	Diversity	Health and welfare	Landscape image	Produce quality	Subsidy independence	Self - sufficiency	Longevity	Risk aversion		
NPK Balances	1	1	1	1			1						1	6	0.24
Profit margin		1		1	1					1		1		5	0.20
Yields		1	1	1						1	1	1		6	0.24
Subsidies		1	1		1					1	1			5	0.20
Diversity	1					1		1						3	0.12
													Total Score	25	

The sustainability attributes in this table are those most commonly used in the literature.
NPK refers to nitrogen, phosphorous and potassium respectively.

Table 6: Aggregate CSI for the conventionally managed farm land over a five year period

Year	Weighted CSI	Equally-weighted CSI
2005	0.396	0.309
2006	0.593	0.667
2007	0.803	0.874
2008	0.484	0.540
2009	0.513	0.590

tool, we recognise it is of little value for such use as currently calculated.

6. Discussion

Rigby *et al* (2000) noted a key advantage of developing sustainability indices; it pulls 'the discussion of sustainability away from abstract formulations' and requires 'explicit discussion of the operational meaning of the term to be revealed': each variable within an indicator needs to be justified. However, this approach reflects a traditional top-down approach in which the variables needed for the index are specified before field work begins. The approach set out here reverses this order of priorities. It identifies those data that are readily available and selects from them the ones which most closely match policy objectives and targets. The example used here clearly suggests that this approach is unlikely to provide a particularly useful measure in the first year as readily available data are unlikely to provide an ideal match with the 'triple-bottom line'. Providing this is regarded as a starting-and not a finishing-point, and given sufficient support to allow development over time, a wider range of variables can be measured from which a more appropriate set can be used to illustrate a farm's sustainability trajectory. This discussion continues with a brief discussion of some of the additional key issues raised by this study.

Indicators and policy goals

It is most likely because of the methodological limitations, that CSIs have not been used by policymakers. The approach advocated here would improve the utility of CSI to a point where they may be considered within cross-compliance obligations or as an option in environmental stewardship scheme. Progress in science and policy is often made from adopting a pragmatic approach based upon a multi-period 'design-action-design' framework (as this is the basis of the scientific approach of observation, hypothesis, experimentation, interpretation leading to a newly formulated hypothesis).

As involvement of farm managers is essential, each needs to gain some advantage from participation. Some farmers will be able to benefit from using sustainability measures to brand products to give them a competitive advantage, or use them to help identify win-win activities on their farm (for example reducing the expensive use of surplus fertilizers). These benefits suggest there will be a pool of farmers who would voluntarily calculate CSI values, but others will need additional incentives. One approach to assist on-farm development would be to provide technical data collection and

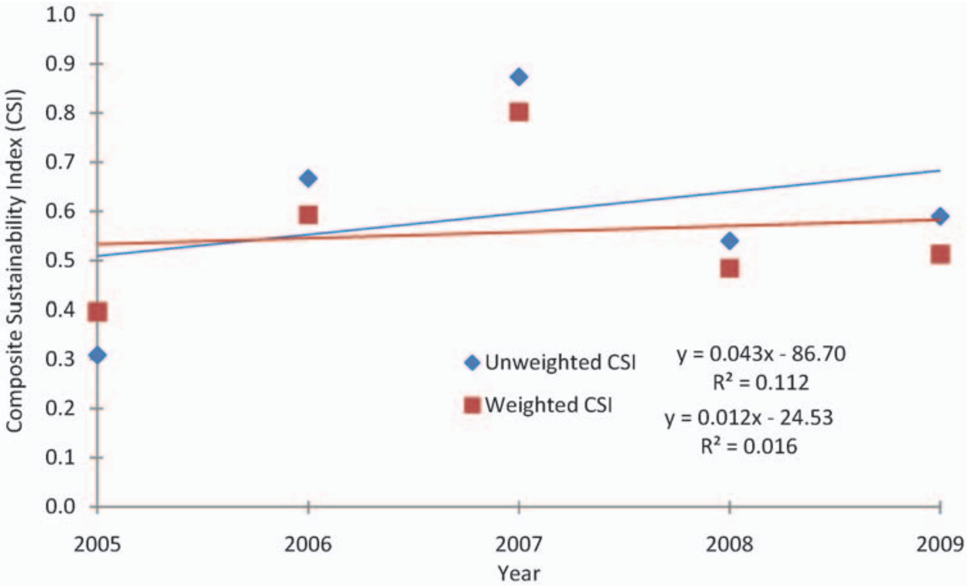

Figure 2: Composite Sustainability Index trends for a conventional dairy system

recording support to a pool of neighbouring farmers who are willing to develop a CSI. This will increase the speed at which the index becomes more useful and the likelihood that farmers will find value by incorporating the environmental consequences of their farm management decisions into their activities.

The inherent difficulties of the indicator-based approach

The inherent difficulties related to the lack of consensus on the definition of 'sustainable agriculture' have proved a barrier to its practical usefulness (Gómez-Limón and Riesgo 2009). However, because the concept of sustainability has remained flexible it has been 'adopted' as a desirable goal by a wide range of stakeholders. Moreover, given the site-specific nature of environmental and rural economy objectives and targets, it is not desirable to select the same set of variables to measure CSI at every location (Bell and Morse 2008)[6,7]. However, it would be desirable to rapidly agree which variables should be collected by farmers from similar eco-systems as this will facilitate inter-farmer data collection efforts. With benchmarking performance within that local pool one can identify those management activities which improve, and those which worsen a farms sustainability index.

Another reason why the reviewed studies use different variables is because the objectives of each study vary. This would not be the case in this use of the CSI as the objective across each farm system would remain constant, but the choice of variables would be more limited than the literature suggests.

Usefulness to policy makers

It is suggested that the operational feasibility of sustainability indicators may be at the expense of technical soundness in its initial years. Crabtree and Bayfield (1998) refer to a report by Ross (1995) which claimed that community input into the development of indicators is required. But they argue that 'the process of developing and using sustainability indicators is an evolutionary one', and that there 'can be no agreed pattern or template for the process'. The present study accepts that location specific initiatives, based on the principles of the active or passive adaptive co-management process, are required to develop more efficient and practical measures of farming's contribution to national sustainability targets.

What this, or indeed any other, approach will not be able to deliver is measurements of the 'unmeasurable' no matter how theoretically sound or policy relevant that measure may be. For example, a CSI might be improved by including a measure that reflects soil health/quality (Nambiar *et al.* 2001) which is a primary indicator of sustainable land management (due to its contribution to plant productivity and impacts on water and air quality (Doran 2002)). However, the definition and measurement of soil health is contested, so in keeping with the philosophy of this study only those variables which are simple to measure would be included. For example, the annual soil vegetative cover (measured as a proportion of the farm area) can be used to as an indicator of the risk of soil erosion, and the extent to which temporary leys are used to improve soil organic matter content.

Usefulness to the farmer

Ultimately the success of this approach to measure sustainability will be judged by the farmer. Whilst the processes of measuring and computing data are unlikely to pose any conceptual problems, the principle of allowing annual changes to the variables included in the index, and its interpretation, may well do. Yet this facet is integral to the potential benefit of this approach. Not only would indices calculated in the initial years likely to be of less value, but farmers would need to have this principle carefully explained because it involves them

[6] For example, water use efficiency is less relevant on (most) UK farms than on farms in arid countries.

[7] Including the use of 'pesticide' might be a sensible indicator to compare conventional farms but it would be inappropriate to use it to compare organic farms.

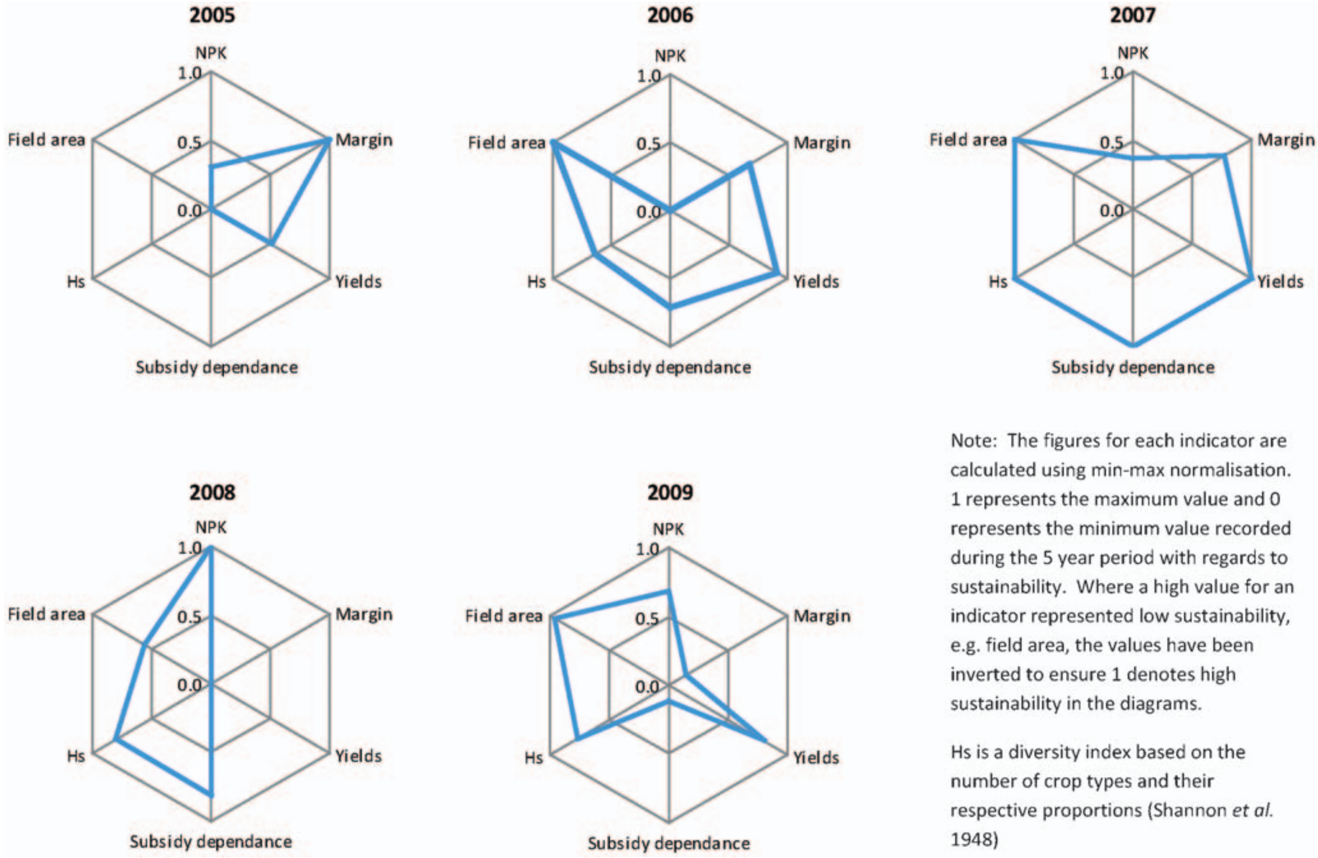

Figure 3: Sustainability webs for a conventional dairy based farm system

making, perhaps initially annual, changes in their compliance activities.

Important to this would be the agreement on the weightings of each variable. Farmers may be mostly interested in the economic viability of their farms, and so would like to assign higher weights to the economic variables however this view is associated with the weak sustainability (Cabeza Gutés 1996) and will not be shared by all stakeholders. It is likely that the weights would be affected by the change in the variables collected each year.

Interpretation of CSIs

All stakeholders would also need to identify which variables can be influenced by factors within the manager's control; there would be little point constructing a farm-specific CSI totally based on exogenous variables. Moreover, some variables will be more predictable than others, for example, annual yields are likely to be more predictable than annual profits. Other indices have problems of interpretation that would need to be addressed. NPK balances can identify nutrient surpluses[8], but does a nutrient deficit equate to the same level of unsustainability as nutrient inputs are suboptimal? (Defra 2010). When interpretation difficulties add to farmers' costs, for example the need for more regular soil tests, some may argue participants need financial support so they are not financially disadvantaged by their voluntary participation in the scheme. However, soil testing to improve nutrient management would result in more accurate nutrient application, thereby crop growth is optimised, nutrients are not wasted and financial savings incurred. Perhaps, financial incentives would be required for measures that do not result in win-wins.

The case study demonstrates how a farm can compute its CSI and present the data using sustainability webs. The example given did not show any specific trend on the farm because farm decisions had not been informed by the availability of the index over those 5 years. However, demonstrating trajectory is an important part of interpreting a CSI so key factors which managers can influence can be identified (Guy and Kibert 1998). Moreover, as annual improvements to data collection are required, some form of on-farm support will be needed initially. In principle, this should not be a problem as financial and advisory support is currently available to facilitate participation into ELS and HLS. In practice finance will likely need to be withdrawn from another programme given current austerity budgets.

Scale of measurement

Traditionally the basic management unit affected by public policy initiatives is the farm holding. Therefore an assessment of sustainability is needed at the farm-level. However, at one extreme, field-level evaluations would illustrate greater variance (but provide greater detail (Castoldi and Bechini 2010)) than the aggregated,

[8] These data are routinely recorded by farms in nitrogen vulnerable zones (NVZ) (a UK legislation targeting high risk areas for nitrate pollution which imposes limits on nitrogen application and involves maintenance of mandatory annual records of fertilise usage), so the data management techniques and processes are well understood and could rapidly be extended to farms in non-NVZ areas.

regional or national level evaluations (OECD 2008). Field scale evaluations may be particularly useful for assessing change in sensitive areas, for example land abutting nature reserves. This would place additional demands on data recording, but would be technically possible; for example, farms in a NVZ must record nutrient balances field by field (Defra 2009).

Problems with the farm-specific composite variables for sustainability

Incorporating the social pillar of sustainability proved a particular problem in calculating the case study CSI. Social variables used in the literature such as 'risk of abandonment of agricultural activity' (Gómez-Limón and Riesgo 2009), 'animal welfare' (Haas *et al.* 2001) and 'consumer taste tests of produce quality' (Reganold *et al.* 2001) provide conceptual and measurement difficulties. They would also be costly to determine on a farm by farm basis. However, variables such as 'subsidy dependency' and 'profitability' are more readily measurable. If variables such as 'contribution to the local economy' and 'percentage of produce sold locally' are considered to be locally important then farmers need robust tools to help calculate them.

Comparisons with other pragmatic approaches

The 'Agri-Environmental Footprint Index' (AFI) is designed to evaluate the effectiveness of agri-environment schemes (Purvis *et al.* 2009). AFIs are directed by policy objectives, so their focus is well-defined and do not include all aspects of sustainability. However, lessons learnt from applying AFI include the need for processes to be participatory and measures to be context specific (Purvis *et al.* (2009); Louwagie *et al.* (2012); (Mauchline *et al.* 2012)). AFI involves a hierarchical process encompassing a set of indicators nested firstly within management practices and then within three aspects of environment: natural resources, biodiversity and landscape. These indicators of management practises and the three aspects of the environment are weighted and summed to produce the single value AFI score (Purvis *et al.* 2009). The aim is to deliver a focused evaluation that is sufficiently flexible to accommodate different farming contexts within a consistent framework; an approach that our study also favours using the triple bottom line as the basic unit of evaluation.

The 'Public Goods Tool' (PGT) has been developed to evaluate farms in organic entry level stewardship (OELS) (Gerrard *et al.* 2012). The tool has a pragmatic approach to producing an easy to understand sustainability web that is inexpensive to produce. Through thorough stakeholder consultation, the authors identified eleven public goods, the delivery of which was assessed by discussions with farmers based on questions and answers and illustrated with graphics. This offers an alternative 'starting point' to our proposed method. The case study shows how important the selection of a starting point is for the speed at which the CSI becomes widely useful, however the PGT is based on scores rather than actual measurements, so may be less accurate and does not consider data availability.

Addressing subjectivity

The literature review shows the subjectivity inherent in different approaches to developing a CSI (Böhringer and Jochem 2007). Many consider it disadvantageous to rely on the views of closely affected stakeholders. The social dimension of sustainable development, and the location specific nature of summary measures, means subjectivity is unavoidable and must be managed rather than eliminated (Kemp and Martens 2007). Subjectivity does not necessarily imply compromise in accuracy and trustworthiness if methods of work allow consistent and robust repeatability across observations (Harper and Kuh 2007). Moreover, as a boundary object, it is not possible to define sustainability without involving a wide range of stakeholders (Castoldi and Bechini 2010). Acknowledging this will help develop not only the initiation of CSIs but also their improvement.

7. Conclusions

Current policy directives and up-coming CAP reforms emphasise the need to develop measurements of farm-level sustainability which have practical value to farmers and policy makers. We have examined the utility of CSI for this purpose, but methodological and data weaknesses mean on-farm CSIs have not been added to the policy-maker's toolkit. Additional improvements are needed, but progress appears to have stalled; though recent initiatives, such as AFI and PGT are offering new approaches to the problem, their widespread application is still limited.

The argument presented here supports their approaches. For agricultural sustainability to have meaning at the farm level it must be measureable, and pragmatic approaches to establishing sustainability measures are required. This would involve a step change in how CSI are conceived and calculated. Rather than aiming to develop an instantly ready-to-use score/value, it is proposed to use that data which is readily available, within a 'design-action-design cycle' dynamic framework. With appropriate support, this pragmatic, bottom-up perspective, will deliver the data improvements needed to allow on-farm CSIs to more closely reflect sustainability and allow convergence between the variables used among similar farms in similar locations. The speed with which this can be done will be critical to the balance between cost and value. It is suggested that the approach outlined be tried out on a voluntary basis initially, with farmers assisted by specialist advisors who can help them compute their farm's CSI and advise on data collection and recording strategies. The availability of grants would assist the process should farmers need to investment in equipment and/or training.

Sustainability webs and CSI values will incorporate change in variables over time and illustrate individual business's trajectory over time and with respect to other businesses. The CSI would help farm managers take account of the effects of their business decisions on the natural and social environment. This improvement would increase the value of the CSI to (i) policy makers, allowing them to be incorporated into with cross-compliance obligations or entry level stewardship of the Environmental Stewardship Scheme and (ii) to farmers within a benchmarking framework, assisting in the spread of best practice and enabling users to identify areas where they can improve.

About the authors

Dr Jeremy Franks is a Senior Lecturer in Farm Business Management at Newcastle University. He teaches second and third year Farm Management modules and has published widely on agri-environmental policy, the economics and marketing of milk, and farm business and farm enterprise analysis.

Ms Poppy Frater is a Masters graduate of Newcastle University with specific interest in the definition and measurement of sustainable production systems. Presently, she works with EBLEX (the beef and sheep levy board) as a Beef and Sheep Scientist.

Acknowledgements

This project would not have been possible without the data and input provided by Dr William Taylor (Nafferton Farm manager) and Ms. Josie Scott (Nafferton farm secretary), to these people we express extreme gratification for the time spent sorting and obtaining the data requested and determining what *can* be included in the sustainability assessment. Additional thanks to Miss Stephanie Cottell, for her support proof reading previous drafts. We are grateful to two anonymous reviewers for their helpful comments on an earlier version of this paper.

REFERENCES

Armitage, D., Marschke, M. and Plummer, R. (2008). Adaptive co-management and the paradox of learning. *Global Environmental Change*, 18(1): 86–98. DOI: 10.1016/j.gloenvcha.2007.07.002.

Bandura, R. (2008). A survey of composite indices measuring country performance: 2008 update.http://web.undp.org/developmentstudies/docs/indices_2008_bandura.pdf.

Barrios, E. and Komoto, K. (2006). Some approaches to the construction of a sustainable development index for the Philippines. *International Journal of Sustainable Development & World Ecology*, 13(4): 277–288. DOI: 10.1080/13504500609469679.

Bartelmus, P. (1999). Green accounting for a sustainable economy: Policy use and analysis of environmental accounts in the Philippines. *Ecological Economics*, 29(1): 155–170. DOI: 10.1016/S0921-8009(98)00086-X.

Bartelmus, P. and Vesper, A. (2000). Green Accounting and Material Flow Analysis. Wuppertal, Wuppertal Institute for Climate, Environment and Energy. http://millennium indicators.un.org/unsd/envAccounting/ceea/archive/Framework/Wupp_GreenAcc_MFA_AlternativesOrComplement.PDF.

Bell, S. and Morse, S. (2008). Sustainability indicators : measuring the immeasurable? London, Earthscan.http://www.worldcat.org/title/sustainability-indicators-measuring-the-immeasurable/oclc/191207723.

Bockstaller, C., Girardin, P., van der Werf, H. M. G., Ittersum, M. K. v. and Geijn, S. C. v. d. (1997). Use of agro-ecological indicators for the evaluation of farming systems. *Developments in Crop Science*, Volume 25: 329–338. DOI: 10.1016/S0378-519X(97)80032-3.

Böhringer, C. and Jochem, P. E. P. (2007). Measuring the immeasurable -- A survey of sustainability indices. *Ecological Economics*, 63(1): 1–8. DOI: 10.1016/j.ecolecon.2007.03.008.

Cabeza Gutés, M. (1996). The concept of weak sustainability. *Ecological Economics*, 17(3): 147–156. DOI: 10.1016/S0921-8009(96)80003-6.

Castoldi, N. and Bechini, L. (2010). Integrated sustainability assessment of cropping systems with agro-ecological and economic indicators in northern Italy. *European Journal of Agronomy*, 32(1): 59–72. DOI: 10.1016/j.eja.2009.02.003.

Cederberg, C. and Mattsson, B. (2000). Life cycle assessment of milk production -- a comparison of conventional and organic farming. *Journal of Cleaner Production*, 8(1): 49–60. DOI: 10.1016/S0959-6526(99)00311-X.

CLA, C., Land and Business Association Ltd) (2009). Carbon Accounting for Land Managers.

Commission, B. (1987). Our Common Future, Chapter 2: Towards Sustainable Development. *World Commission on Environment and Development (WCED)*. Geneva: *United Nation*.

CoolFarmInstitute (2012). Cool Farm Tool.

Crabtree, B. and Bayfield, N. (1998). Developing sustainability indicators for mountain ecosystems: a study of the Cairngorms, Scotland. *Journal of Environmental Management*, 52(1): 1–14. DOI: 10.1006/jema.1997.0159

Darnhofer, I., Bellon, S., Dedieu, B. and Milestad, R. (2010). Adaptiveness to enhance the sustainability of farming systems. A review. *Agron. Sustain. Dev.*, 30(3): 545–555.

Defra (2009). Guidance for farmers in Nitrate Vulnerable Zones. E. A. Defra. 1.

Defra (2010). Fertiliser Manual (RB209) 8th Edition. Surrey, TSO.https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69469/rb209-fertiliser-manual-110412.pdf.

Doran, J. W. (2002). Soil health and global sustainability: translating science into practice. *Agriculture, Ecosystems & Environment*, 88(2): 119–127. DOI: 10.1016/s0167-8809(01)00246-8.

Eckert, H., Breitschuh, G. and Sauerbeck, D. R. (2000). Criteria and standards for sustainable agriculture. *Journal of Plant Nutrition and Soil Science*, 163(4): 337–351. DOI: 10.1002/1522-2624(200008)163:4<337::aid-jpln337>3.0.co;2-3.

Esty, D. C., Levy, M., Srebotnjak, T. and De Sherbinin, A. (2005). Environmental sustainability index: benchmarking national environmental stewardship.http://www.yale.edu/esi/

Franks, J. (2010). Boundary organizations for sustainable land management: The example of Dutch Environmental Co-operatives. *Ecological Economics*, 70(2): 283–295. DOI: 10.1016/j.ecolecon.2010.08.011.

Gerrard, C. L., Smith, L., Pearce, B., Padel, S., Hitchings, R., Measures, M. and Cooper, N. (2012). Public Goods and Farming. *Farming for Food and Water Security*: 1–22. DOI: 10.1007/978-94-007-4500-1_1.

Gómez-Limón, J. A. and Riesgo, L. (2009). Alternative approaches to the construction of a composite indicator of agricultural sustainability: An application to irrigated agriculture in the Duero basin in Spain. *Journal of Environmental Management*, 90(11): 3345–3362. DOI: 10.1016/j.jenvman.2009.05.023.

Grêt-Regamey, A. & Kytzia, S. (2007). Integrating the valuation of ecosystem services into the Input-Output economics of an Alpine region. *Ecological Economics*, 63, 786–798. DOI: 10.1016/j.ecolecon.2007.02.026.

Guy, G. B. and Kibert, C. J. (1998). Developing indicators of sustainability: US experience. *Building Research and Information*, 26: 39–45. DOI: 10.1080/096132198370092.

Haas, G., Wetterich, F. and Köpke, U. (2001). Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. *Agriculture, Ecosystems & Environment*, 83(1-2): 43–53. DOI: 10.1016/S0167-8809(00)00160-2.

Halberg, N., Verschuur, G. and Goodlass, G. (2005). Farm level environmental indicators; are they useful?: An overview of green accounting systems for European farms. *Agriculture, Ecosystems & Environment*, 105(1-2): 195–212. DOI: 10.1016/j.agee.2004.04.003.

Hani, F., Braga, F., Stampfli, A., Keller, T., Fischer, M. and Porsche, H. (2003). RISE, a Tool for Holistic Sustainability Assessment at the Farm Level. *International Food and*

Agribusiness Management Review, 06(04).http://purl.umn.edu/34379.

Harper, S. R. and Kuh, G. D. (2007). Myths and misconceptions about using qualitative methods in assessment. *New Directions for Institutional Research*, 2007(136): 5–14. DOI: 10.1002/ir.227.

Hodge, R. A. and Hardi, P. (1997). The need for guidelines: the rationale underlying the Bellagio principles for assessment.http://www.iisd.org/pdf/bellagio.pdf.

Izac, A. and Swift, M. (1994). On agricultural sustainability and its measurement in small-scale farming in sub-Saharan Africa. *Ecological Economics*, 11(2): 105–125. DOI: 10.1016/0921-8009(94)90022-1.

Jansen, D. M., Stoorvogel, J. J. & Schipper, R. A. (1995). Using sustainability indicators in agricultural land use analysis: an example from Costa Rica. *Netherlands Journal of Agriculural Science*, 43, 61–82. https://library.wur.nl/ojs/index.php/njas/article/view/585.

Kates, R. W., Parris, T. M. and Leiserowitz, A. A. (2005). What is sustainable development? Goals, indicators, values, and practice. *Environment(Washington DC)*, 47(3): 8–21. DOI: 10.1080/00139157.2005.10524444.

Kemp, R. and Martens, P. (2007). Sustainable development: how to manage something that is subjective and never can be achieved? *Sustainability: Science, Practice, & Policy*, 3(2): 5–14.http://sspp.proquest.com/archives/vol3iss2/0703-007.kemp.html.

Legg, W. (2006). Policy efforts to achieve sustainable agriculture: an OECD perspective. Agriculture and climate beyond 2015. F. Brouwer and B. McCarl, Springer Netherlands. 46: 265–277. DOI: 10.1007/1-4020-4368-6_15.

Lindeijer, E. (2000). Biodiversity and life support impacts of land use in LCA. *Journal of Cleaner Production*, 8(4): 313–319. DOI: 10.1016/S0959-6526(00)00025-1.

López-ridaura, S., Keulen, H. V., Ittersum, M. K. v. and Leffelaar, P. A. (2005). Multiscale Methodological Framework to Derive Criteria and Indicators for Sustainability Evaluation of Peasant Natural Resource Management Systems. *Environment, Development and Sustainability*, 7(1): 51–69. DOI:10.1007/s10668-003-6976-x.

Louwagie, G., Northey, G., Finn, J. A. and Purvis, G. (2012). Development of indicators for assessment of the environmental impact of livestock farming in Ireland using the Agri-environmental Footprint Index. *Ecological Indicators*, 18(0): 149–162. DOI: 10.1016/j.ecolind.2011.11.003.

Mauchline, A. L., Mortimer, S. R., Park, J. R., Finn, J. A., Haysom, K., Westbury, D. B., ... Yli-Viikari, A. (2012). Environmental evaluation of agri-environment schemes using participatory approaches: Experiences of testing the Agri-Environmental Footprint Index. *Land Use Policy*, 29(2): 317–328. DOI: 10.1016/j.landusepol.2011.07.002.

MetOffice (2011). from www.metoffice.gov.uk/.

Nambiar, K. K. M., Gupta, A. P., Fu, Q. and Li, S. (2001). Biophysical, chemical and socio-economic indicators for assessing agricultural sustainability in the Chinese coastal zone. *Agriculture,Ecosystems & Environment*, 87(2): 209–214. DOI: 10.1016/S0167-8809(01)00279-1.

OECD (2008). Handbook on Constructing Composite Indicators : Methodology and User Guide. Paris, Organisation for Economic Co-operation and Development.http://www.NCL.eblib.com/EBLWeb/patron?target=patron&extendedid=P_367134_0&.

OECD (2008). Measuring Sustainable Production, OECD Publishing. DOI: 10.1787/9789264044135-en.

Pacini, C., Wossink, A., Giesen, G., Vazzana, C. & Huirne, R. (2003). Evaluation of sustainability of organic, integrated and conventional farming systems: a farm and field-scale analysis. *Agriculture, Ecosystems & Environment*, 95: 273–288. DOI: 10.1016/S0167-8809(02)00091-9.

Pimentel, D., Hepperly, P., Hanson, J., Douds, D. & Seidel, R. (2005). Environmental, Energetic, and Economic Comparisons of Organic and Conventional Farming Systems. *BioScience*, 55, 573–582. DOI: 10.1641/0006-3568(2005)055[0573:EEAECO]2.0.CO;2.

Plummer, R. (2009). The adaptive co-management process: An initial synthesis of representative models and influential variables. *Ecology and Society*, 14(2): 24.http://ibcperu.org/doc/isis/11750.pdf.

Pretty, J. (2008). Agricultural sustainability: concepts, principles and evidence. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1491): 447–465. DOI: 10.1098/rstb.2007.2163.

Purvis, G., Louwagie, G., Northey, G., Mortimer, S., Park, J., Mauchline, A., ... Peltola, J. (2009). Conceptual development of a harmonised method for tracking change and evaluating policy in the agri-environment: The Agri-environmental Footprint Index. *Environmental Science & Policy*, 12(3): 321–337. DOI: 10.1016/j.envsci.2009.01.005.

QIU Hua-jiao, CHANG Xin, CHENG Xu and ZHU Wan-bin (2005). The Analysis and Design of Agricultural Sustainability Indicators System. *Scientia Agricultura Sinica*, 6(4): 475–486. DOI: 10.1016/S1671-2927(07)60072-8.

Reganold, J. P., Glover, J. D., Andrews, P. K. and Hinman, H. R. (2001). Sustainability of three apple production systems. *Nature*, 410(6831): 926–930.http://dx.doi.org/10.1038/35073574.

Rigby, D. and Cáceres, D. (2001). Organic farming and the sustainability of agricultural systems. *Agricultural Systems*, 68(1): 21–40. DOI: 10.1016/S0308-521X(00)00060-3.

Rigby, D., Woodhouse, P., Young, T. and Burton, M. (2001). Constructing a farm level indicator of sustainable agricultural practice. *Ecological Economics* 39(3): 463–478. DOI: 10.1016/S0921-8009(01)00245-2.

Rist, L., Campbell, B. M. and Frost, P. (2013). Adaptive management: where are we now? *Environmental Conservation*, 40(01): 5–18. DOI: 10.1017/S0376892912000240.

Rodrigues, G. S., Rodrigues, I. A., Buschinelli, C. C. d. A. and de Barros, I. (2010). Integrated farm sustainability assessment for the environmental management of rural activities. *Environmental Impact Assessment Review*, 30(4): 229–239. DOI: 10.1016/j.eiar.2009.10.002.

Ross, T. (1995). Sustainability indicators research project: consultants; report of the Pilot Phase Luton. *Local Government Management Board*.

SAI (2010). Sustainable Agriculture Initiative; Food for thought. Retrieved 31/05/2011, 2011, from http://www.saiplatform.org/sustainable-agriculture/definition.

Sands, G. R. and Podmore, T. H. (2000). A generalized environmental sustainability index for agricultural systems. *Agriculture, Ecosystems & Environment*, 79(1): 29–41. DOI: 10.1016/S0167-8809(99)00147-4.

Speelman, E. N., López-Ridaura, S., Colomer, N. A., Astier, M. and Masera, O. R. (2007). Ten years of sustainability evaluation using the MESMIS framework: Lessons learned from its application in 28 Latin American case studies. *International Journal of Sustainable Development and World Ecology*, 14(4): 345–361. DOI: 10.1080/13504500709469735.

Van Der Werf, H. M. G., Tzilivakis, J., Lewis, K. & Basset-Mens, C. (2007). Environmental impacts of farm scenarios according to five assessment methods. *Agriculture, Ecosystems & Environment*, 118, 327–338. DOI: 10.1016/j.agee.2006.06.005.

Wackernagel, M. and Rees, W. E. (1996). Our ecological footprint : reducing human impact on the earth. Gabriola Island, BC; Philadelphia, PA, New Society Publishers.

White, M. S. (2013). Sustainability: I know it when I see it. *Ecological Economics*, 86(2): 213–217. DOI: 10.1016/j.ecolecon.2012.12.020.

Williams, A. G., Audsley, E. & Sandars, D. L. (2006). Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. *In:* DEFRA (ed.) *Defra Research Project IS0205*, Bedford: Cranfield University and Defra. http://www.britishpoultry.org.uk/wp-content/uploads/2012/07/GWP_project_Defra_ISO205.pdf.

Wossink, G. (1995). Environmental economics of the farm firm.

Zahm, F., Viaux, P., Girardin, P., Vilain, L. and Mouchet, C. (2006). Farm Sustainability Assessment using the IDEA Method. Bern, International Forum on Assessing Sustainability in Agriculture (NFASA). http://ibcperu.org/doc/isis/mas/9968.pdf#page=90.

Appendix: List of potential sustainability indicators rated by ease of application

Indicator	Methods/definition	Difficulty rating* (0-10) 0=extremely difficult, 10=extremely easy	
		Conventional	Organic
Variable costs	Expenses (£) that change in proportion to productivity	10	10
Profit	Product gains (£) less all costs	2	2
Profit per hectare	Real value of agricultural production minus the real cost per Ha	9	9
Product revenue	Return per product (£ per unit)	9	9
Compensation payments	Single farm payment (£)	9	9
Agri-environment payments	Environmental stewardship and countryside stewardship schemes (£)	9	9
Energy Balance	Kcals/ha using input/output focus (Sum of the energy in petrol, lubricants, pesticides, fertilisers, seeds and machinery - energy of the crop above ground biomass)	2	2
Balance of N in soil	The difference between N contained in the inputs (fertiliser, manure) and outputs (crops) (kg N/ha)	10	10
Balance of P in soil	The difference between P contained in the inputs (fertiliser, manure) and outputs (crops) (kg P/ha)	10	10
Balance of K in soil	The difference between K contained in the inputs (fertiliser, manure) and outputs (crops) (kg K/ha)	10	10
Adverse impacts of pesticides	Using the Environmental yardstick for pesticides (EYP) (Reus and Leendertse, 1999) based on active chemical ingredients half life and Koc value (sorption coefficient of the pesticide) as well as site specific soil and meteorological conditions using simulation programming.	2	2
CO_2- emissions	CO_2 is estimated from fuel and electricity use.	8	8
CH_4- emissions	CH_4- is estimated from the number of livestock multiplied by emissions factors for western Europe (IPCC 1996) (in CO_2-equivalents for GWP_{100})	8	8
N_2O- emissions	N_2O is based on number of livestock, N excretion of animals (kgN/animal/yr) and the fraction of this N that is manure N (%/100) estimated from animal waste handling method (IPCC 1996). Field burning of agricultural residues; characteristics (IPCC 1996 worksheet 4-4). Emissions from soils are estimated from synthetic fertiliser use, fraction of synthetic fertiliser N applied that volatilizes, area of cultivated organic soils, fraction of N that leaches.	2	2
Crop rotation indicator	Average suitability of each previous-successive crop combination rated 0-10. E.g continuous successions of the same crop given a low score. Companion cropping given high score.	4	4
Biodiversity; Number of grassland species	Index 1-5 (≤22=5, 23-25=4, 26-28=3, 29-31=2, ⩾32=1)	4	4
Biodiversity; Time of first cut	Index 1-5 (5 May=5, 10 May=4, 15 May=3, 20 May=2, 25 May=1)	8	8
Biodiversity; density of hedges and field margins	Relative frequency Index 1-5 (low=5, average=3, high=1)	4	4
Biodiversity; diversity of hedges and field margins	Index 1-5 (low=5, average=3, high=1)	7	7
Biodiversity; state/care of hedges and field margins	Index 1-5 (poor=5, average=3, very good=5)	7	7
Biodiversity; fences	Index 1-5 (none=5, medium density small fences=3, high density broad fences=5)	4	4
Length of grazing period	Length of grazing period and the typical look of the cattle and the layout of the farmstead (garden, trees, orchard) (two separate indicators) (scored 1-5)	10	10
Farmstead layout	Proportion of the farmstead that is the same as it was 40 years ago (%) or score from 1-5 how traditional the farmstead is.	9	9
Crop diversity	The quantity of different crop types on farm that occupy an area greater than 0.25 ha.	8	8
Specialisation	% of land covered by principle crop	8	8
Mean area per plot	Mean size of the fields that make up the farm (ha)	8	8
Soil cover index	% of soil cover by crops in one year (averaged over the four seasons)	4	4
Farm yard manure application	On what proportion of the farm is farm yard manure applied? (%)	8	8
Soil Erosion	Movement of soil (t/km^2)	1	1
Soil Quality	Several measurements, E.g. Bulk density (cm^3), Cation Exchange Capacity (CEC), Nutrient concentrations (%).	2	2
Seed Source;	Proportion conventional/organic (%)	9	9
Seed source; own farm supplied	Proportion sourced on site (%)	10	10

Appendix: Continued

Indicator	Methods/definition	Difficulty rating* (0-10) 0=extremely difficult, 10=extremely easy	
Farm self-sufficiency; Calve replacement	What proportion of the calf replacements are from the farm? (%)	9	9
Farm self-sufficiency; fertiliser	What proportion of the fertiliser is sourced on farm? (%)	10	10
Abiotic resource use	Includes most metals, many minerals, fossil fuels and uranium for nuclear power. Quantified in terms of the mass of the element antimony (Sb). Information required; Abiotic resources used and relative quantities.	4	4
Land use	Yields are scaled up or down using linear coefficients derived from Moxey et al (1995) for different land grades. Required information; land grade and respective yields.	8	8
Crop Yield	Direct yield (kg/ha)	10	10
Animal housing system and conditions, herd management	For example heard management is rated according to lightness, spacing, grazing season and care (1-5) according to specific thresholds.	5	5
Agricultural employment	Hours on farm divided by area (hours/ha)	4	4
Stability of workforce	% of the demand for labour during critical periods. The higher the value for this indicator the less stable is the population in rural areas.	4	4
Risk of abandonment of agricultural activity	Index constructed to a range from a maximum of 1 (farmer less than 55 years old on above average income) to 0 (farmer more than 70 years old and below average income)	9	9
Economic dependence on agricultural activity	% of farmer's income derived from agriculture. Higher dependence, higher stability.	7	7

*Ratings provided by farm manager