Evaluation of techniques for measuring and assessing environmental impacts of agriculture

John Tzilivakis

A thesis submitted in partial fulfilment of the requirements of the
University of Hertfordshire for the award of the degree of
Doctor of Philosophy Based upon Published Work

This programme of research was carried out in the
Agriculture and Environment Research Unit (AERU) at the University of Hertfordshire
in collaboration with ADAS, Brooms Barn Research Station, LEAF and
Rothamsted Research.

March 2005

UH

Abstract

This thesis describes a programme of research that has aimed to improve our capability to assess the environmental impacts of agriculture. The candidate has conducted the work described and contributions by co-authors are acknowledged but not discussed (see Appendix A for co-author statement). A number of different measurement and assessment techniques have been applied to a range of different agricultural situations. This included developing some of these techniques as part of this research. This has liberated a number of findings that could advance our knowledge and understanding of the environmental impacts of agriculture and help improve the tools we have to measure and assess them. A case study approach has been taken and includes:

- Use of indicators as simple tools for assessing whole farming systems at the national level and their development and application to the farm level.
- Development and application of modelling techniques to assess the activity of pesticide use, by comparing different crop protection regimes used in integrated farming and conventional systems.
- Development and application of energy accounting techniques to assess energy use and emissions of greenhouse gases from a range of activities in the production of sugar beet.
- Application of a combination of techniques, pesticide and nutrient modelling and energy and financial accounting, to assess the impacts of a specific crop (sugar beet).
- Development and application of a risk assessment framework for assessing potential risks to soil and it functions.
- Development and application of a strategic environmental assessment technique to assess the impacts of agricultural policy, particularly focusing on techniques assessing significance of impacts in terms of actual damage and techniques for handling uncertainty and confidence issues.

The studies described in this thesis have all had their own individual objectives, but in combination they are starting to construct a wider more holistic picture of the environmental impact of agriculture. There are undoubtedly still fuzzy areas that are

not fully understood and in other places there are complete gaps in knowledge and understanding, such as impacts on biodiversity and human health. However, the picture we have now is certainly better than it was only 10 years ago and there is no reason why it shouldn't improve as our knowledge and understanding evolves and as our measurement and assessment tools improve. The work undertaken in this thesis has provided a step forward in this evolution and has presented some novel ideas that could have potential to be further developed in the future. A key issue will be to understand how we use the tools and techniques available to construct the same picture for different audiences, and avoid any conflicting images between policy and farm level. It will be important to be able to integrate tools and techniques to develop holistic perspectives and ensure that they draw upon the same data sources. This is entirely feasible with modern information technology.

List of submitted publications

1. Newbold, M. J., Lewis, K. A., **Tzilivakis**, J., Finch, J, Kähö, T. M., Skinner, J. A. and Bardon, K. (1997) Options for informal environmental management: the agricultural industry highlighted. *Eco-Management and Auditing* **4**, 22-27

2. **Tzilivakis**, J. and Lewis K.A. (2004) The development and use of farm level indicators in England. *Sustainable Development* **12**, 107-120

3. **Tzilivakis**, J., Turley, D. B., Ogilvy, S. E., Lewis, K. A. and Lawson, K. (2004) Assessing the environmental impact of crop protection strategies for integrated farming systems. *Agronomie* **24**, 67-76

4. **Tzilivakis**, J., Jaggard, K., Lewis, K. A., May, M. and Warner, D. J. (In press) Assessment of the energy inputs and greenhouse gas emissions in sugar beet (Beta vulgaris) production in the UK. *Agricultural Systems* In press (available online at: www.sciencedirect.com)

5. **Tzilivakis**, J., Jaggard, K., Lewis, K. A., May, M. and Warner, D. J. (2005) Environmental Impact and Economic Assessment for UK Sugar Beet Production Systems. *Agriculture, Ecosystems and Environment* **107**, 341-358

6. **Tzilivakis**, J., Lewis K. A. and Williamson, A. R. (2005) A prototype framework for assessing risks to soil functions. *EIA Review* **25**, 181-195

7. **Tzilivakis**, J., Broom, C., Lewis, K. A., Tucker, P., Drummond, C. and Cook, R. (1999) A Strategic Environmental Assessment Method for Agricultural Policy in the UK. *Land Use Policy* **16**, 223-234

Contents

Acknowledgements

I would like to acknowledge the contributions of all the co-authors on the submitted publications and the organisations that funded the research, which includes the Department for Environment, Food and Rural Affairs (DEFRA), the Environment Agency and the British Beet Research Organisation (BBRO). I would also like to thank Dr Kathy Lewis and Professor Ranjeet Sokhi for the valuable supervision they provided.

1.0. Introduction

1.1. Background and rationale

Agricultural production needs to be multi-functional in terms of the goods and services it provides. It is not only about the production of food, fibre, oils and biomass. It must also function as a habitat for biodiversity, a buffer and filter for pollutants and satisfy the demands of society in terms of the landscape it creates and any environmental pollution or damage it causes. In order to achieve this we need to be able to fully understand the environmental impacts of agriculture. This is no easy task when you consider the diversity of activities on farms, the materials and energy they utilise and how this is interwoven with a range of habitats, biodiversity and environmental media. The potential environmental effects are numerous and can have a range of direct and indirect impacts, both positive and negative.

We are faced with constructing a very complex picture of agriculture and its environmental impact. A picture that needs to be understood by all the stakeholders including farmers, scientists, policy makers and consumers. Farmers need to able to understand the impacts their activities have on the environment and be able to respond not only to market and consumer demands, but also to legislation. The combination of green consumer demands and legislation, for example cross compliance (Council Regulation EC 1782/2003), waste framework directive (Council Directive 91/156/EEC) and water framework directive (Directive 2000/60/EC), are steering farmers towards more proactive environmental management. It is therefore important that farmers are able to understand the impacts of their activities. In turn, policy makers need to understand the impact of their policies and regulations to ensure that they are achieving the desired objective and not causing new problems in the process. Consumers also demand information about the environmental impacts of the products and services they purchase and consume. There can also be more local demands from the public on the impact of agricultural activities in their 'backyard', as illustrated by recent calls for increased buffer zones next to residential areas when spraying pesticides and a review of bystander exposure (RCEP, 2004).

Our scientific understanding of the issues has grown over the past half century, since the time of Rachel Carson and her landmark book *Silent Spring* in 1962 (Carson, 1962). But just as our knowledge has grown so have the environmental issues facing agriculture. It is somewhat inevitable, that as the industry adapts and evolves to meet multiple objectives, new issues appear over the horizon. It is essential, therefore, that the industry is able to understand the problems and respond to resolve them. Thus in recent years there has been some focus on developing techniques to measure and assess the impacts in order to improve our understanding and construct sustainable solutions, from the policy level to the farm level.

It is not practical to measure and monitor all environmental impacts of agriculture. There are limitations to the time and money available for such activities. Consequently EIA techniques are required to provide a practical and cost-effective alternative. The techniques available have limitations in their ability to assess environmental impacts, so it is important to assess their capabilities within the agricultural sector, a sector in which they are relatively untested.

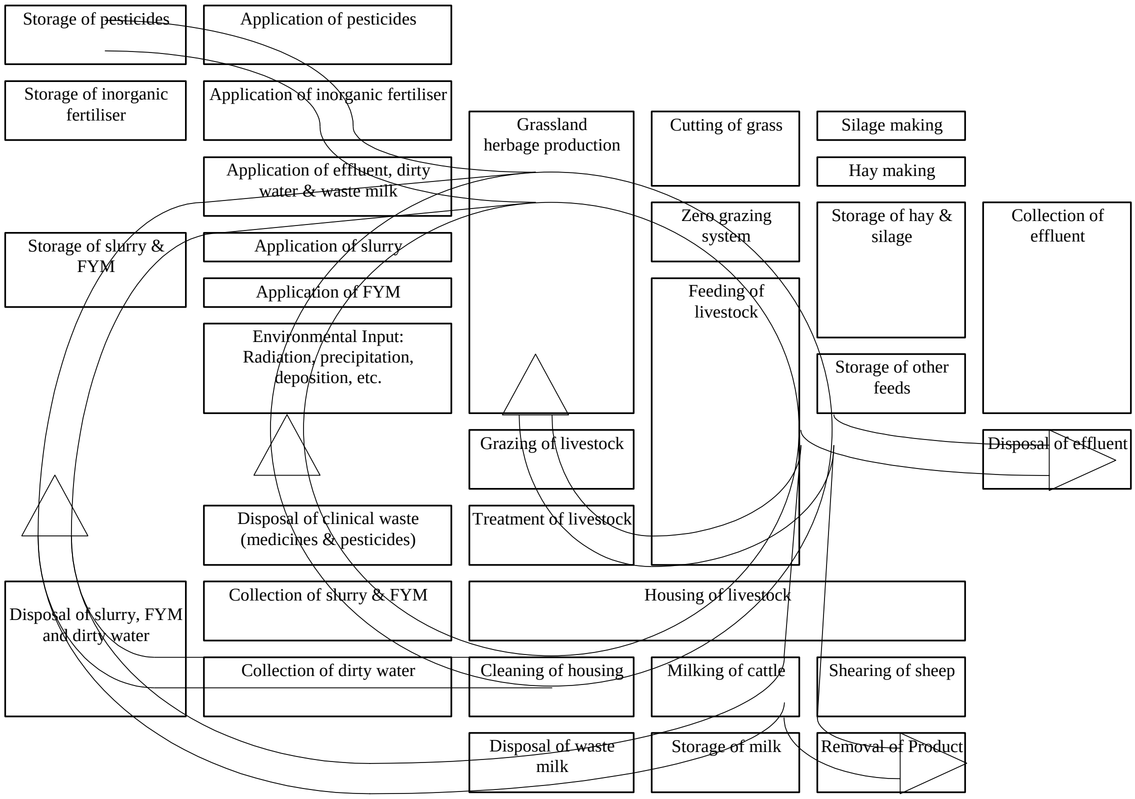
1.2. Setting the scene

1.2.1. A systems perspective of agriculture and the environment

In terms of resource use, agriculture is similar to any other industry in that the aim is to maximise efficiency of use, minimising use of non-renewable resources and any impacts that arise from the production of inputs. However, in terms of effects and impacts from the production process, agriculture is not like other industries. Whereas other industrial facilities have to deal with end-of-pipe issues, agriculture is more embedded and integrated into the environment, indeed the environment is analogous to the factory floor. Consequently, there are many direct effects on environmental media used in the production process and also many diffuse and indirect effects.

As a starting point we can try to understand the flows of materials and energy within the production system. Figure 1 illustrates this for a livestock farm (sheep and dairy).

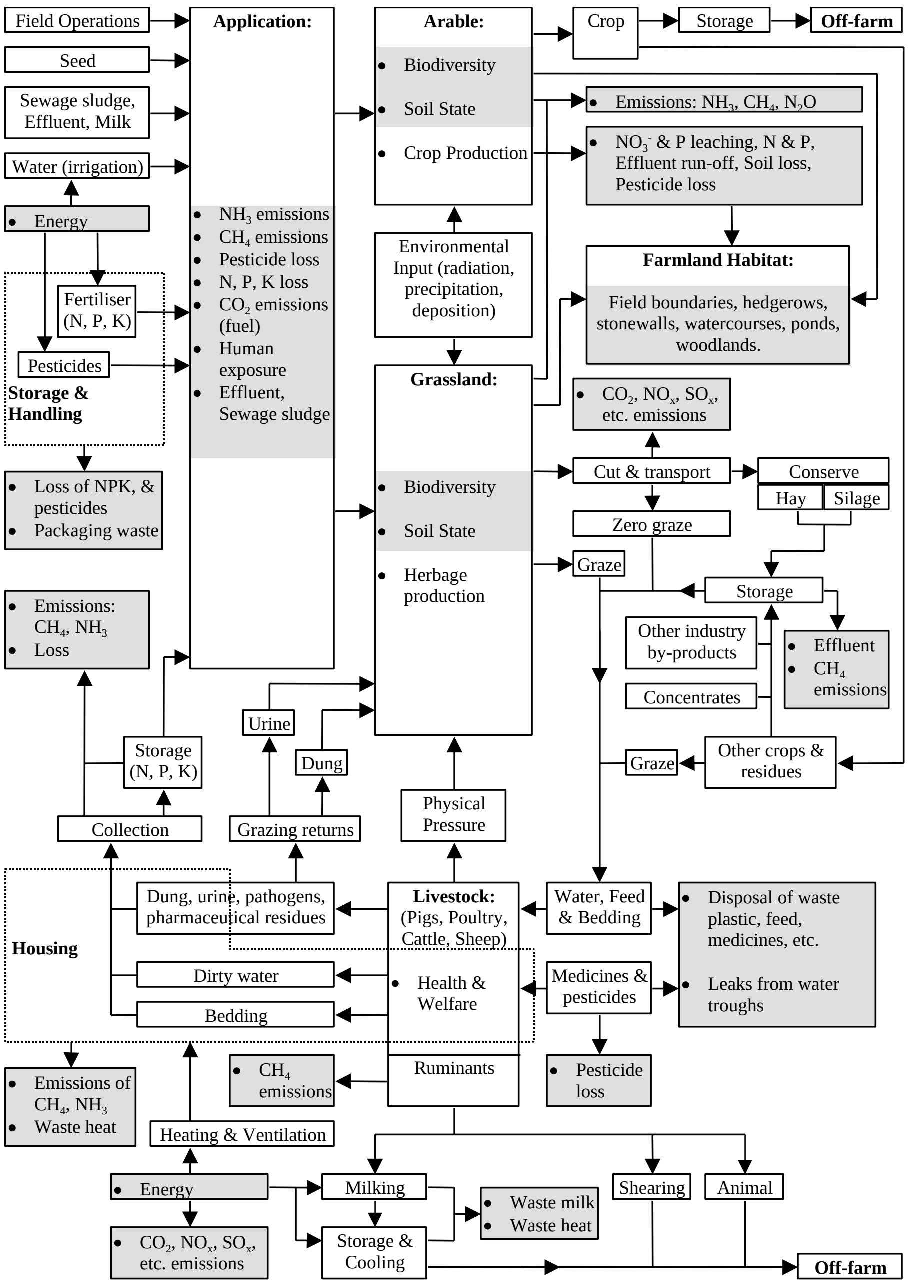
Figure 1. Flows of materials and energy in a farm system



The diagram illustrates that there are a number of components within a farm system that utilise materials and energy as part of the production process. There are various external inputs, such as agrochemicals and fuel. There are also environmental inputs in terms of solar radiation, water, soil and nutrients. These inputs are then used in the production process to generate outputs, in terms of products such as milk, meat and fibre and also waste. Finally, some of the materials and energy are recycled back into the production system, such as nutrients in slurries and manure. If we were to add arable cropping into this system it adds to the complexity of what needs to be understood.

Throughout the production process there are various points where environmental effects and impacts can arise. Figure 2 shows the flows of materials and energy for a mixed farm and highlights where environmental effects might arise within the production system.

Figure 2. Flows of materials and energy and environmental effects



(Tzilivakis and Lewis, 1999)

The process of understanding the system is only the first step. It only identifies the activities, the energy and materials being used. These need to be quantified and qualified in terms of the amounts, the effects, the receptors affected and ultimately the end impact.

1.2.2. Measurement and assessment

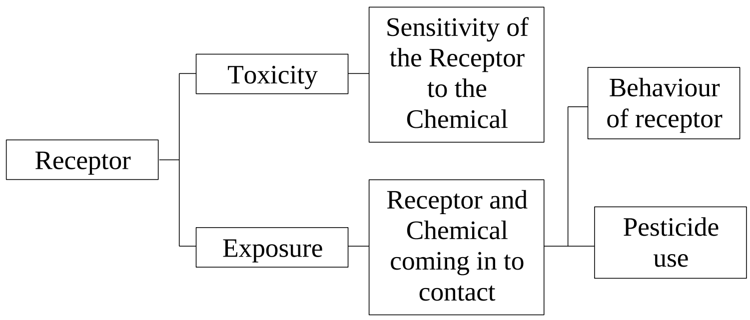
In any environmental assessment quantitative data are a valuable commodity due to the detail they reveal. Quantitative data can be obtained either from actual measurements or derived from models. Actual measurements are typically made in experimental circumstances such as in the recent farm scale evaluations of genetically modified herbicide tolerant crops (Firbank et al., 2003). However, this is not always practical under other circumstances as it can be very expensive, the farm scale evaluations cost in excess of 1 million Euros per crop (Perry et al., 2004). Consequently, we often rely on modelling to generate quantitative data. This may be of lower quality, but this can be satisfactory as models are often based on original experimental data. If measured or modelled data are not available, another option is to use expert judgement to obtain 'soft' qualitative data in the absence of 'hard' quantified information. Qualitative information can range from a collection of observations through to just anecdotal information and expert judgement. But even anecdotal information can shed light if it fills a gap. The picture may not be as sharp as it would with quantitative data but it is better than no picture at all. Environmental risk assessment (DOE, 1996, Environment Agency, 2000, Green et al., 2000) often makes use of such ‘soft’ data. Risk factors are a good example. We have some knowledge of soil erosion, for example, and the factors that tend to lead to its occurrence. These factors can be observed and risk assessment made. This will not quantify the amount of soil lost or potentially lost but will provide some indication of the degree of risk by using scoring or ranking techniques, for example. Scoring and ranking techniques have been used in numerous environmental assessment contexts, particularly in environmental performance assessments to provide a measure of something that is not directly measurable (Robinson, 1996).

Once we have a set of data (quantitative or qualitative) it needs to be assessed in relation to an impact assessment endpoint. Typically this might relate to something valued by society or which is a concern (Suter, 1990; Hunsaker et al., 1990), for example:

- Food Production
- Human health and safety
- Wildlife and biodiversity
- Landscape
- Climate change
- Resource depletion
- Air, water and soil quality

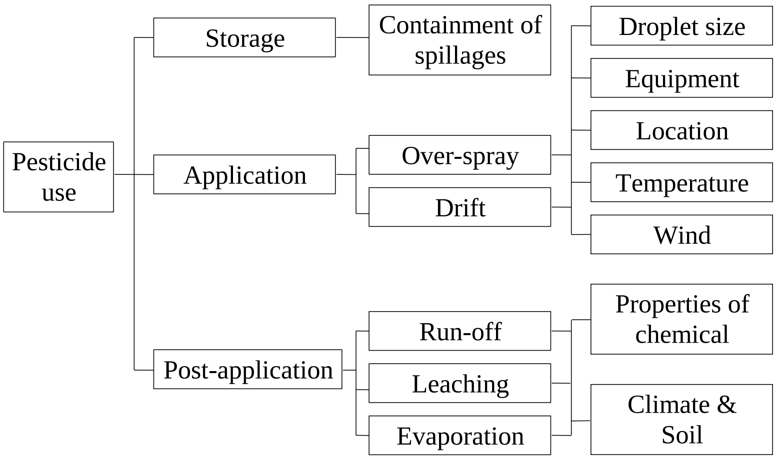
It is not always possible to directly measure end impacts and so we often have to correlate measured effects to end impacts (Andersson et al., 1994). It is also important to understand causal components and the linkages between them (Cheung, 1994; Johnson, 1993). For example, the impact of a pesticide on a particular species (receptor) is determined by the toxicity of that pesticide to the receptor (Hart et al., 2003) and the quantity that the receptor comes into contact with, i.e. the exposure (Brown et al., 2003). The exposure is partly determined by the behaviour of the receptor and the way the pesticide is used (see Figure 3).

Figure 3. Causal factors in the impact of pesticides on a receptor



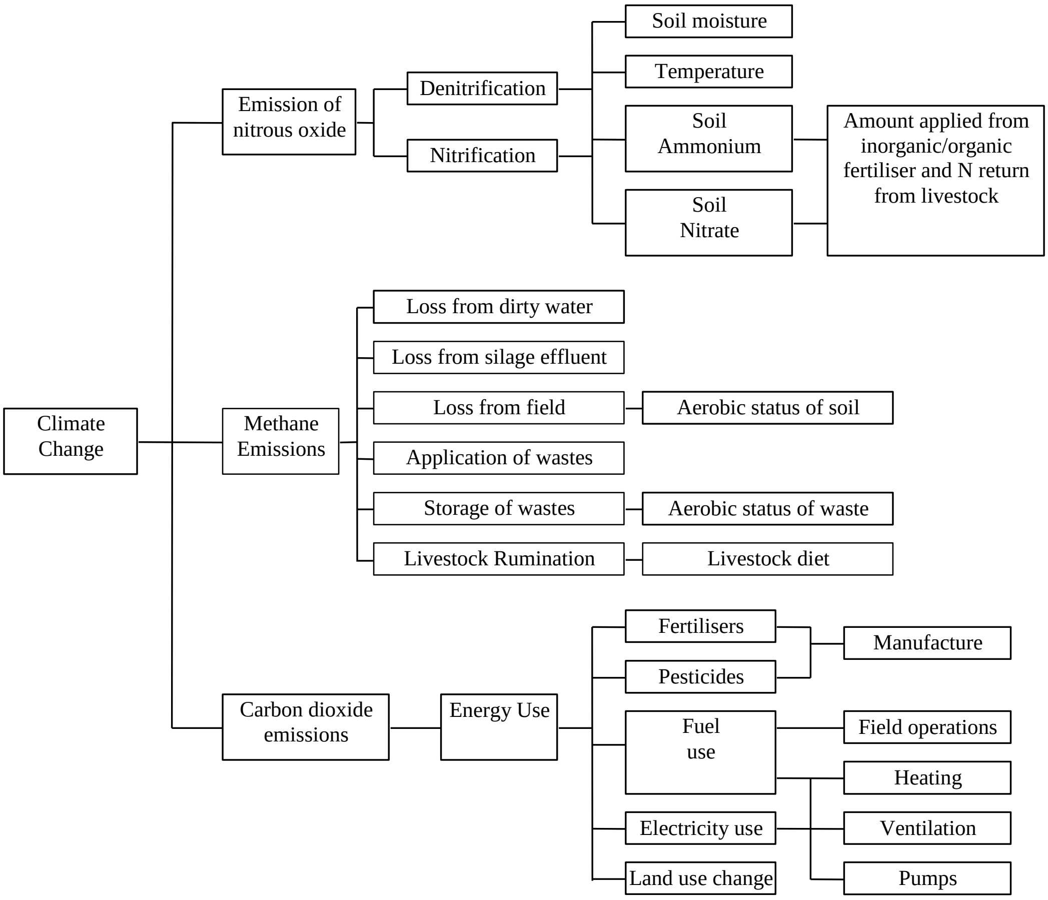
The behaviour relates to where the organism is located in relation to the fate and transport of the pesticide. For example, if a bird species tends to feed in a middle of a field it may have a greater chance of coming into contact with a spray than another species that prefers to feed in the field boundary (Hart et al., 2003). The way the pesticide is used is more within the control of the farmer, this is explored in further detail in Figure 4.

Figure 4. Causal factors environmental impact of pesticide use



There are many issues relating to storage, application and post-application. All of these can affect exposure of the pesticide to a range of different receptors. Although this does not look complex, there are many factors hidden with each of the boxes in Figures 3 and 4. Figure 5 is a similar diagram for the emission of greenhouse gases.

Figure 5. Causal factors in the emissions of greenhouse gases and climate change



When Figures 3, 4 and 5 are considered in combination with Figure 2, the depths and complexity of any study start to become apparent. It is not unsurprising that many studies have tended to focus on specific activities or issues, rather than whole systems.

Clearly any tools and techniques that aid the process of measuring and assessing the environmental impacts of agriculture would be valuable as we attempt to reveal the depths and breadths of this complex issue.

2.0. Description of the Research

2.1. Aims and objectives

This research aims to improve our capability to assess the environmental impacts of agriculture in terms of the tools and techniques available to scientists and also other stakeholders in the agricultural industry such as policy makers and farmers. A number of appropriate measurement and assessment techniques will be identified, developed and applied to a range of different agricultural situations. The techniques will then be critically evaluated to obtain the following objectives:

- to identify barriers and limitations involved in applying the techniques to agriculture;
- to evaluate any novel solutions devised; and
- to identify areas for improvement and ways forward.

This should liberate a number of important findings that advance our knowledge and understanding of the environmental impacts of agriculture and help improve the tools we have to measure and assess them.

Section 1 has illustrated the complexity of the agriculture and environment in terms of the breadth and depth that needs to be tackled. Consequently, to assess the capability of different tools and techniques they need to be tested and assessed under a range of agricultural situations. A case study approach has therefore been taken to this research and is outlined in section 2.2 and how each of the submitted publications fit into this approach is outlined in section 2.3. The case studies are then critically evaluated in the discussion (section 3).

2.2. Overview of the methodology

The approach taken was to firstly review the techniques available to the agricultural sector in terms of the tools for assessing and managing environmental impacts and consequently those that could be further explored and applied within this study. Appropriate literature and EIA methods were reviewed to identify key issues with respect to their application within agriculture. This resulted in **Submitted Publication 1**.

A series of case studies were then undertaken to apply, develop and evaluate the measurement and assessment techniques identified in the review and explore their use in different agricultural situations. In some instances the approaches taken are novel and developed specifically for the case studies. They attempt to explore the techniques from different perspectives including:

- indicators (simple measures representative of the wider picture)
- single activity (pesticide use)
- single issue (energy use)
- crop (sugar beet)
- environmental media (soil protection)
- policy (strategic environmental assessment)

The case study approach resulted in **Submitted Publications 2 to 7**. A number of conclusions, drawn from the case study findings, highlight where novel approaches have overcome many of the issues identified in the review. Issues that still need to be resolved and where further research, development and improvement is required have also been identified in this process.

2.3. Coherence of the submission

Submitted Publication No. 1 forms part of a review of EIA techniques and their applicability to agricultural situations. The other 6 publications form a case study approach to applying and testing EIA measurement and assessment techniques.

Submitted Publication No. 2 deals with indicators, which are simple and practical tools used commonly at the policy level, but in this instance they are explored by applying national indicators to the farm level. This paper reveals that tools used for measurement and assessment can also have another role in terms of knowledge transfer and promoting good practice. They also potentially provide a common perspective from the farm to the policy level, which has been lacking in the past. Indicators though are often too simplistic and do not address some issues with sufficient depth and complexity to reveal the true picture.

Submitted Publication No. 3 considers an activity perspective, with the example of pesticide use. This paper illustrates how, with a narrow focus, the depths and complexities of the impact of a particular activity can be assessed. However, the narrow focus can sometimes fail to observe that some impacts are the result of numerous activities. This is explored in **Submitted Publication No. 4,** which assesses energy use for a range of farm activities. Despite the broad range of activities, the focus of the paper is still quite narrow and thus a holistic perspective is still lacking. This is addressed in **Submitted Publication No. 5,** which takes a crop perspective, with the example of sugar beet. This produces a sustainability profile for sugar beet production scenarios. However, this holistic and comprehensive study still overlooks some important issues, such as impacts on soil. This is due to the lack of a scientific assessment framework, a common problem when dealing with issues relating to soil protection. This is explored in **Submitted Publication No. 6,** which takes an environmental media perspective, with the example of soil protection. A key part of this paper deals with how to handle qualitative information and expert judgement and incorporate this into a knowledge base for assessing risks to soil functions. Assessing, handling and communicating the uncertainty and confidence was part of this. This was also an important aspect in **Submitted Publication No. 7**, which takes a policy perspective, with example of strategic environmental assessment.

In both **Submitted Publications 6 and 7** scoring and ranking techniques were used to assess uncertainty and confidence. The techniques in **Submitted Publications 6 and 7** were both novel prototypes and are both too cumbersome to be applied as practical tools. However, they do attempt to address the issue of impact assessment, which is lacking in **Submitted Publications 2 to 5**.

3.0. Discussion

3.1. Setting the context

It is important to recognise and remember the context of any environmental assessment, i.e. what questions is the assessment attempting to answer and who is asking the questions. These two aspects have a fundamental influence on the assessment in terms of its boundaries, its breadth and depth, and on how the findings are communicated.

Setting the boundaries of any particular study is very important as it sets the perspective for what we are looking at. Our view can range from the micro to the macro, from the microbiological processes in a particular soil to agriculture globally and all the possibilities in between. These may include:

- The functions of a particular soil
- A particular practice or activity (e.g. pesticides)
- A particular crop (e.g. sugar beet)
- An individual farm
- A farming system (e.g. IFS vs. conventional)
- Farms within a catchment or region
- The whole of UK agriculture
- Agriculture globally

When considering these different perspectives, there can be a range of reasons for requiring an environmental impact assessment. Typically these include:

- diagnosing or preventing problems (on a specific farm or farms generally)
- comparison of different options/practices (on a single farm)
- comparison of different systems (on a range of farms)

These usually fall into the context of a decision making process, be it at the policy level or the farm level. The basic framework is essentially the same at both levels. We gather information about agricultural practices and environmental impacts. This information is analysed and used to make decisions that influence agricultural practices and their environmental impact. This process then repeats as we review and refine our decisions and actions (similar to the Driving Force, Pressure, State, Impact, Response

(DPSIR) framework developed by the EEA, 1999). The difference between the policy and farm level is the degree specificity. At the policy level generalisations are made and agricultural units are classified or aggregated into homogenous groups and generic solutions (policies) are developed to tackle issues. Whereas at the farm level the problems/issues tend to be more site specific and demand more specific solutions.

Agricultural practices can have a range of direct and indirect effects on the environment. These include point and non-point source pollution from agrochemicals, impacts on soil quality, greenhouse gas emissions and direct effects on wildlife habitats and biodiversity (Skinner et al., 1997). These are complex, diverse and inter-linked issues requiring measurement and assessment to formulate knowledge that has a fundamental effect on the solutions devised to manage them. This is the same be it devising policy solutions or making practical farm management decisions. Thus it is important to fully understand how such knowledge and information is derived and how it feeds into the process of diagnosis and management.

Environmental Impact Assessment (EIA) tools and techniques have been used in a range of other industries often as part of an environmental management system. Thus this is the main area to examine to draw potential measurement and assessment tools that could be applied to agriculture. Consequently the first step is to review what is available, identify appropriate measurement and assessment techniques and identify the key issues for their application to agriculture.

3.2. Review of available tools and techniques

Submitted Publication 1 provides a brief introduction to a number of different techniques and their applicability to agriculture. These include some common measurement and assessment techniques such as calculating emissions, use of surrogate or indicator measures, assessment of risk and impact significance. A number of issues were identified that must be considered in the application of the techniques to agriculture including:

1. The need for a holistic picture
2. Lack of data
3. Lack of scientific understanding
4. Uncertainty and confidence
5. Masking of data and impact assessment findings

It is also important to understand the context of the assessment and the questions it is trying to answer. Information can be used and presented in different ways depending on the purpose of the assessment and the end audience for the findings.

In hindsight the review was too narrow as it excluded other techniques that were new, more conceptual and less mainstream at the time. This included environmental accounting concepts such as food miles and ecological footprints, for example.

Food miles is more of an indicator than an actual technique, nevertheless it was not included in the review when perhaps it should have been. Food miles is a measure of the distance food has travelled from its place of production to its point of retail and ultimate consumption. This gives an indication of the degree of transportation involved for different products and thus consumption of fossil fuels. Sustain (2001) have undertaken one of the more comprehensive studies using food miles. However, there have been no studies evaluating food miles as a technique or measure and understanding its role in relation to assessing the environmental impact of agricultural production systems. Food miles, and its relation to fossil fuel consumption, does relate to the ecological footprint concept which has been more widely studied.

The concept of ecological footprints was created in the early 1990's (WWF, 2004c) and is a measure that indicates natural resource consumption. The footprint is usually expressed as the total area of land required for food and fibre production, absorbing waste and provision of space for infrastructure. This can be calculated for different activities, businesses, countries or the whole planet. For example, WWF (2004a) have calculated a global Ecological Footprint of 13.5 billion global hectares in 2001, or 2.2 global hectares per person. WWF have compared this to the Earth's biocapacity in 2001, based on its biologically productive area, which they calculate to be approximately 11.3 billion global hectares, or an average of 1.8 global hectares per person. Thus illustrating a concern over the sustainability of our production and consumption patterns. This has also been calculated for the UK (Barratt and Simmons, 2003), which has a per capita footprint of 5.45 hectares, which is clearly larger than the 1.8 available globally.

One of the advantages of the ecological footprint is its simplicity for communication as it is easily understood. It has metaphorical resonance, as recognised by Barrett and Scott (2001), in that the idea of a footprint can be easily associated with environmental impact. There have been numerous academic developments and applications of the technique, many based on the methodology of Wackernagel and Rees (1996) which as been further developed and applied (Wackernagel et al., 1999; Monfreda et al., 2004 and Wackernagel et al., 2004). The methodology has also been modified to incorporate economic elements, such as the input-output approach developed by Bicknell et al. (1998) and applied by McDonald and Patterson (2004). The technique does have it limitations and these centre around it being over-simplistic in some circumstances (as highlighted by van den Bergh and Verbruggen, 1999) and validity of the data (Haberl et al., 2001 and Haberl et al., 2004).

Clearly there has been a lot work on these techniques during the period of time of this research and this could have made a contribution to this study. However, the roles of ecological footprints and food miles are perhaps more beyond the farm gate in terms of assessing the impacts of society as a whole and not just agriculture on its own. If they were applied to agriculture alone the study would be too narrow for the technique and results may be meaningless, and possibly misleading, as it would only provide just a part of the whole picture. Consequently their exclusion from the review has not been a major detriment to this research. Indeed ecological footprints could potentially draw upon some of the techniques evaluated in this study.

3.3. Use of indicators in environmental assessment

When presented with complex systems to understand, monitor and diagnose it is desirable to limit the amount of information to that which is strictly necessary to obtain a valid picture. This is particularly the case for policy makers who have a desire to keep things simple, but also for time-constrained businesses, such as farmers. Consequently indicators can be an appealing tool to utilise.

Indicators are one of the simpler approaches to measuring and assessing environmental impacts and typically exist as a suite of indicators to cover different subject areas (DEFRA, 2004; Forestry Commission, 2002; OECD, 2004). However, it is important to recognise when a measure is an indicator and not just another measurement in a wider assessment. This can be something of a philosophical discussion and there are a plethora of definitions as Rigby et al. (2001) discovered. However, at a basic level environmental indicators are typically simple measures that are understood to be representative of a wider or more complicated picture.

In 2000, the UK government launched a national pilot set of 35 indicators for sustainable agriculture in Great Britain (MAFF, 2000). However, as policy tools, many of these indicators are highly technical in nature and often appear relevant only at national level. Consequently, the key messages underpinning the indicators can easily become lost at farm level. The work undertaken for **Submitted Publication 2** attempted to address this issue by making these indicators more applicable to the farm level. The project involved breaking down the national data by geographical location and farm type. It was felt that in order to drive progress towards sustainability it was important to define indicators at a level meaningful to the target audience and that encapsulates the spatial and temporal diversity of the farm environment.

The research disaggregated the national set and created some supplementary measures, resulting in a suite of 42 indicators. A number of communication products were then developed to raise awareness amongst farmers, including case study sheets, a cassette tape and computer software. These were piloted by LEAF (Linking Environment And Farming) farmers to gain feedback. This feedback revealed one of the key findings of the study. At the farm level the most important aspect of the indicators was the key messages behind them, in terms of good agricultural practice, rather than the indicator values and trends. This finding is supported by Rigby et al. (2001) who also found that indicators helped raise awareness and discussion about important sustainable development issues. This finding also raises a question of the usefulness of the actual indicator values. The context of their use is perhaps the critical factor. At the farm level the indicator values may provide a simple snap shot picture or may be of anecdotal value. But in many instances they are too simple or abstract to be used within the decision making and management of the farm. This is due to the origin of the indicators, i.e. they were designed for the policy level. Indicator measures that have more practical applications are more likely to be used at the farm level. A good example is the use of previous cropping records to indicate the nutrient status of the soil.

Another aspect to consider is the role of indicators in impact assessment. MAFF (2000) categorise the indicators into 3 types, Driving Force, State and Response, following the structure developed by the OECD (OECD, 1994), which has been further developed into the DPSIR framework (EEA, 1999). A key problem though is correlating indicators of pressure and/or response, with indicators of state and impact. We have indicators recording the activities and practices on farms and indicators monitoring the state of, and impact on, the environment. However, there is not always a clearly established causal relationship between a change in an indicator of practices and a change in an indicator of state or impact. This is recognised by both Halberg et al. (2004) and van der Werf and Petit (2002). Rigby et al. (2001) also notes that indicators tend to be constructed according to patterns of input use rather than their impacts. This is further complicated by the fact that indicators do not indicate what is sustainable or unsustainable as recognised by Hueting and Reijnders (2004).

Submitted Publication 2 did not review the quality of the indicators and their appropriateness for the task. The set indicators were given by Department for Environment, Food and Rural Affairs (DEFRA) so there was no opportunity to review the indicator selection process. This paper would have benefited from a discussion on what are good and poor indicators and how to develop and select appropriate measures. However, this is perhaps something for future research when the indicators themselves will be subject to review (MAFF, 2000).

The quality of the data and level of uncertainty in indicator values is also something that is often overlooked. The process of disaggregating the national indicators by geographical location and farm type revealed that the quality of the data on which the national indicators were based was poor in many instances. However, this was never reflected at national level. Some attempts were made to convey confidence and uncertainty in the paper (e.g. pesticide monitoring data), but this confidence assessment was not extended to all the indicators. Given the original quality of the data this is something that perhaps should have been attempted in this work, but was not possible in the time and resources available.

One of the more problematic indicators is pesticide use and its impact on the environment. Although it is highly monitored in terms of use, area sprayed, levels in rivers and groundwater, none of these convey the actual impact of the active substances. For example, since the 1980's the amount of pesticide used decreased and has remained relatively level since (MAFF, 2000). However, this does not necessarily indicate a decrease in impact because some pesticides used in small quantities may be more toxic than others used in large quantities. Similarly, the amount of pesticide detected in rivers has also decreased recently with a 23% reduction in samples over 0.1 μg/l in 2003 (Environment Agency, 2004). Such a decline does not necessarily indicate an improvement in agricultural practices, such as those promoted by the Voluntary Initiative (CPA, 2004), the package of measures introduced to avoid the imposition of a pesticide tax. Climatically the autumn of 2003 was very dry (Environment Agency, 2004) and so less pesticide will have been washed of crops and soil into watercourses, contributing to the apparent decline in pesticides in rivers. It should also be remembered that over the past 10 years many pesticides have been revoked for use, due to the ongoing EU review of pesticides (Council Directive 91/414/EEC) and this could have an influence on what is detected.

3.4. Environmental risk assessment of pesticides

The complex issue of the impact of pesticides and how to measure them has been studied for many years and there have been many techniques developed to measure them, such as those reviewed by Reus et al. (1999 and 2002). One of these techniques, p-EMA (Brown et al., 2003; Hart et al., 2003; Lewis et al. 2003 - see appendix D), has been further developed and refined since 1999 and was used in **Submitted Publication 3**. In this study p-EMA was applied retrospectively to the LINK Integrated Farming Systems (IFS) project that was undertaken over 5 cropping years from 1993 to 1997 (Ogilvy et al., 1994). In 1993 environmental impact assessment techniques were in their infancy, so differences in crop protection strategies could only be evaluated using the quantity of pesticide applied. So in 2002 the p-EMA software was used to re-evaluate the data. Applying the technique retrospectively was not ideal because the original data were not collected for the purposes of the p-EMA model. Consequently some interpretation had to be made on the data. For example, field conditions at the time of the IFS study were not recorded in sufficient detail as required by the p-EMA model, so assumptions had to be made based on historical climate records for the locations of the IFS study sites. This was a not a problem for the purposes of this study, but it could have an influence on what the actual impact was compared to that which is modelled.

The results of this study showed that using the quantity of pesticide applied as a surrogate indicator of risk is unsound, and that where the site has few sensitive habitats there may be little difference in predicted environmental impact between the different crop protection strategies. However, if the site is habitat-rich, IFS strategies can significantly lower the predicted risk. The results also demonstrated the need for substantial site and pesticide information to improve IFS strategies.

This study is limited to assessing just the risks to biodiversity, represented by a range of taxa. It does not cover wider impacts such as those on human health via pesticides entering the food chain, be it through drinking water or food. Margni et al. (2002) attempted to take a wider perspective using a Life Cycle Assessment (LCA) approach. However, in taking a wider approach they have had to compromise their assessment by not taking a site-specific approach to determining impacts, unlike the approach taken in this study with p-EMA. Additionally, they also recognise that assessing impacts to humans can only be done using a simplified linear effect-damage relationship which is not necessarily appropriate or correct for all impacts (as discussed in **Submitted Publication 7**).

Submitted Publication 3 also illustrates how some significant findings can be easily masked within the assessment due to the way the data are analysed, assessed and presented. The p-EMA system addresses the issue of risk communication by providing different levels of information that the user can drill down through depending on their requirements.

Another important element to this study was that the assessment covered the whole rotation. The rotation aspect acknowledges the temporal dimension of the system, an important consideration to take into account. On-farm strategies, decisions and practices all have temporal components and consequent effects and impacts. For example, certain sequences of crops in the rotation can increase or decrease the pest pressure on subsequent crops and thus the need for chemical intervention (or other forms of control) that could have a potentially negative impact. For example, mechanical weeding may consume more energy.

3.5. Energy use and greenhouse gas emissions

Reducing the energy derived from fossil fuels within agricultural systems has important implications for decreasing atmospheric emissions of greenhouse gases that contribute to climate change. Therefore the identification of crop production methods that maximise energy efficiency and minimise greenhouse gas emissions is important. In **Submitted Publication 4** such a study for the UK crop of sugar beet was undertaken. Energy balance techniques described in Hülsbergen and Kalk (2001) were used to analyse thirteen production scenarios that represented about 90% of the UK beet crop. **Submitted Publication 5** describes how these scenarios were created. The study revealed that the overall energy input of the UK beet crop ranges between 15.7 and 25.9 GJ/ha. It produces between 7.3 and 15.0 times as much energy in dry matter at the sugar factory gate as consumed in its production, with an average of 9.7. Global warming potential (GWP) ranged from 0.02 to 0.04 eq. t CO_2 per tonne of clean beet harvested. These figures are comparable to those of Hülsbergen and Kalk (2001) and more recently Bennett et al. (2004).

The results of the study were expressed on both a per tonne of yield and a per hectare basis. The per hectare basis is useful as it allows comparison with other crops (as undertaken in **Submitted Publication 5**). The per tonne of yield basis is more important for comparing different production systems of the same crop, i.e. sugar beet in this instance. This revealed the importance of yield in relation to energy input (and other environmental burdens in **Submitted Publication 5**). The organic scenario (XIII) was a good example of this. Although the energy input was average (19 GJ) compared to the conventional scenarios, its low yield (34 tonnes/ha) meant that its energy efficiency was the worst of the 13 scenarios. The longer distance the organic beet had to travel to the processing factory (as only one factory in the UK was processing organic beet at the time of the study) was a contributory factor. The higher energy use for field operations, such as mechanical weeding, was also a factor (as supported by Leake, 2000). This can be problem for lower yield systems, such as organic. Flessa et al. (2002) compared greenhouse gas emissions from conventional and organic systems in Germany also found on a per hectare basis organic was better, but not so on a per tonne of yield basis. Bailey et al. (2003) also found differences when examining the results on an area and yield basis for the IFS study (Ogilvy et al., 1994) explored in **Submitted Publication 3**. Clearly this is an important aspect when presenting the results of environmental assessments of crops and production systems. This is perhaps something that could have been explored in more detail in this study.

Data availability and quality was a critical issue in this study. Calculating the energy use, not only for on-farm activities but also for the production of all the inputs, required obtaining the data from the few studies which have actually measured these and in some instances these figures were measured over 20 years ago. Data needed to be extrapolated whilst still ensuring that it remained realistic. For example, there are few data on the energy input for the production of individual pesticide active ingredients. Instead average figures are used for the herbicides, fungicides and insecticides, based on similar chemistry in their production (Pervanchon et al., 2002, take the same approach). There is likely to be some differences between active ingredients within any particular group, but this data is not available. Additionally, emission factors were used for calculating greenhouse gas emissions based on the fuel types used for different activities. Emissions were then converted to global warming potential (GWP). Clearly there is scope for errors to accumulate. This is something that perhaps should have been assessed within this study, but was not due to limitations on time and resources.

As acknowledged in **Submitted Publication 3** it is important to explore different production systems over a rotation. This was not undertaken in this study because it was beyond the scope and the resources of the project. It would have been desirable to assess the energy use over the whole rotation, including sugar beet in a similar way to Bailey et al. (2003). Consequently, this study is limited in respect to temporal considerations.

As noted above, the work of Bailey et al. (2003) was undertaken on the same IFS study as **Submitted Publication 3**. Each study has its own focus, i.e. energy and pesticides respectively. However, when assessing the environmental impact of a crop or production system a more holistic perspective is required. It would be an interesting exercise to combine the results of Bailey et al. (2003) and those of **Submitted Publication 3**, but this would still only cover energy and pesticides. There are other aspects that can be assessed and these are explored in **Submitted Publication 5**, which provides a more holistic perspective building on the work of **Submitted Publication 4.**

3.6. Environmental assessment of sugar beet

The study of energy use in UK sugar beet production was part of larger study to assess the environmental impacts of the crop (**Submitted Publication 5**). As well as examining energy use and GWP, the study assessed nitrate leaching and denitrification using SUNDIAL (Smith et al., 1996) and pesticide ecotoxicity. A net margin was also calculated for each scenario to add an economic element to the analysis, thus tackling two of the pillars of sustainability (environment and economic, the third being social). Pesticide ecotoxicity was calculated using the p-EMA model and was calculated for a range of theoretical habitat descriptions and then again for a habitat description based on an aerial survey of sugar beet fields in the UK. Of the nine measures made for each scenario, six were chosen as the key performance measures. These were net margin, GWP, energy efficiency, nitrate leaching, denitrification and pesticide ecotoxicity.

In order to provide an easy means of comparing the scenarios, each of the measures was performance indexed. This is done by expressing the value for each scenario as a fraction (0 to 1) of the maximum value across all scenarios, or where the smallest figure is desirable the inverse is calculated (i.e. 1 minus the fraction of the maximum). This process generates a normalised set of performance scores similar to a performance matrix that is used in many multi-criteria analysis (MCA) techniques (Dodgson et al., 2000). However, unlike MCA techniques, no weightings were placed on the scores. This helps maintain the objectivity of the results by avoiding any subjectivity creeping into the weighting. The technique used though does facilitate weighting if it were required, for example it could be implied that the economic performance should have equal weighting to the environmental performance, whereas the moment there are 5 environmental measures and only 1 economic measure. If the performance index for Net Margin is multiplied by five then has an equal weight to all the environmental performance scores, thus providing a 50:50 perspective. Figures 6a and 6b provide and example of this based on Figures 2a and 2b from **Submitted Publication 5**.

Figure 6a. Weighted sustainability profile comparing the performance of the scenarios on a per hectare basis

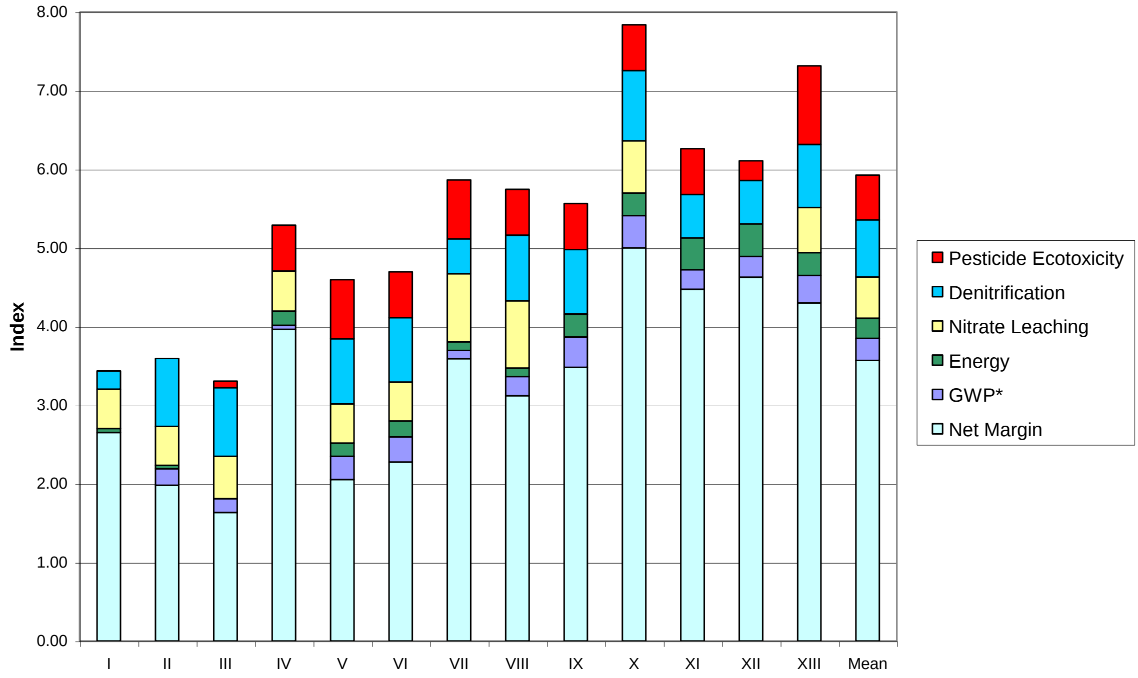
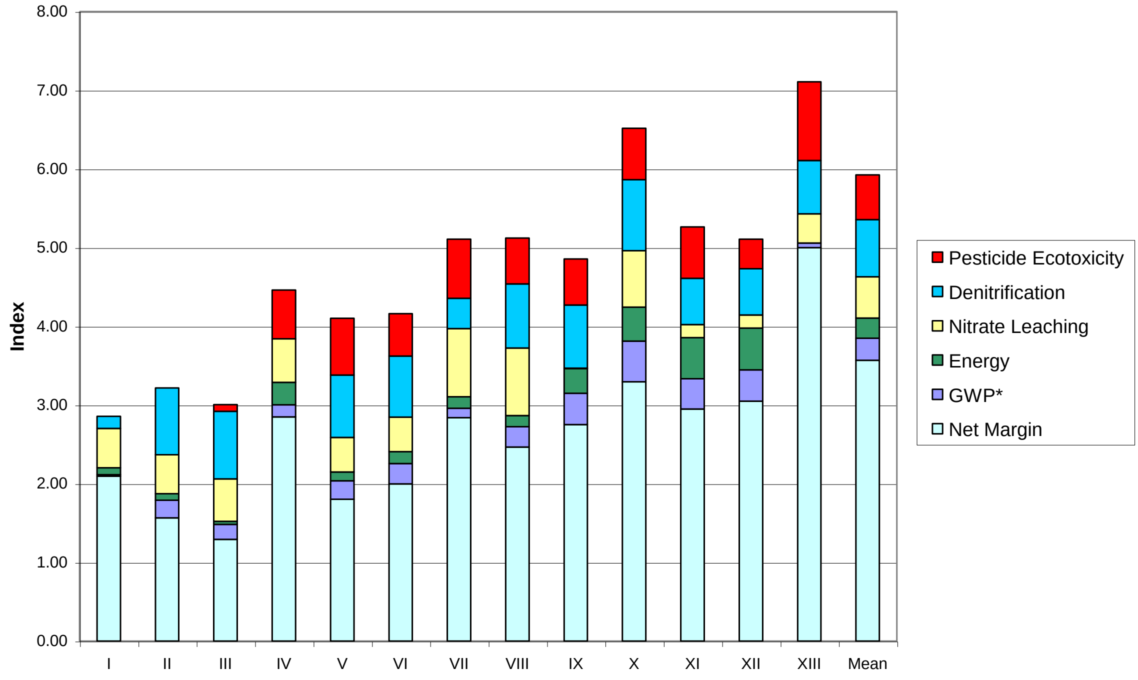


Figure 6b. Weighted sustainability profile comparing the performance of the scenarios on a per tonne of yield basis



* GWP = Global Warming Potential

Consequently, this approach could be used to not only weight economic and environmental performance, but also to weight different environmental components. Each environmental performance parameter could conceivably be weighted based on the value society places on it. For example, if pesticides and global warming were of more concern than nitrate leaching then these parameters could have a higher weight and this would be reflected in the relative performance profiles of the scenarios. This is already evident if you compare Figure 6b above with Figure 2b (in **Submitted Publication 5**), the extra weighting given to economic performance means that scenario X is no longer the best overall performer, the organic scenario is boosted by it economic premium per tonne.

As discussed above this study did not assess the impacts of sugar beet over a complete rotation due to limitations in the scope and resources of the project, so it is limited in that respect. It also did not include a genetically modified (GM) herbicide tolerant sugar beet scenario. This would have been desirable as it would have allowed a comparison of the 12 conventional scenarios with that of the GM variety. A GM scenario was not included as the farm scale evaluations (Firbank et al., 2003) were still in progress and important environmental impact data were not available, such as impacts on biodiversity. However, Bennett et al. (2004) have undertaken a study that compares GM with conventional, but the number of scenarios was limited to five (3 in the UK, 2 in Germany) compared to the 13 used within **Submitted Publication 5**. Bennett et al. (2004) found that the GM crop would be less harmful to the environment and human health than growing the conventional crop, largely due to smaller emissions from herbicide manufacture and field operations.

One of the reasons for undertaking this study of sugar beet is that there are alternative crops for producing sugar, such as sugar cane. There are also alternatives for producing biofuels. The support mechanisms for growing sugar beet in the EU are also under review. Consequently this project is timely in supplying valuable information to these debates. The EU sugar regime was introduced in 1968 and extended in 2001 (Council Regulation EC/1260/2001) and had the original aim to provide guaranteed markets and prices for sugar. This regime is currently being reviewed and a new sugar policy must be operational by 1 July 2006. The reforms are likely to be a phasing out or cuts to the quota system, a reduction of the internal market price and a lowering of the import tariff

(EFRAC, 2004 and Kirkman, 2004). The RBU and RAC (2004) have explored the consequences of a cut in quota and price and they conclude that this would lead to decline in the production of sugar beet, farm incomes and biodiversity. The decline in biodiversity is largely attributed to the value of spring cropping and stubbles and the impacts of the replacement by winter cereals. The conclusions of RBU and RAC (2004) could be complimented by the work undertaken in **Submitted Publication 5**.

A reduction in the amount of sugar produced from sugar beet may result in more cane sugar being imported and consumed in the UK. The environmental consequences of this are not known, as there have been no studies undertaken for sugar cane similar to the study undertaken for sugar beet in **Submitted Publication 5**. A study undertaken by de Carvalho Macedo (1996) is almost comparable, but this focused on the production of bioethanol and only examined greenhouse gas emissions. More recently Borrero et al. (2003) have also explored environmental aspects of sugar cane production. However, they are also focused on alcohol production and use an environmental efficiency concept (impacts in relation to productivity) rather than actual environmental impact, within the context of an environmental management approach. WWF (2004b) do examine sugar beet and sugar cane together, but not to the same depths as **Submitted Publication 5**. WWF take a more global perspective examining the issue of sugar production using a case study approach, claiming that sugar may be responsible for more biodiversity loss than any other single crop. It is a very political issue and an area that would benefit from a substantial amount of objective research comparing all sugar production methods equally. An LCA approach from cradle to grave may be the best option to assess the impacts across the full life cycle of sugar production. The LCA approach could also be extended to cover biofuel production, utilising work such as that undertaken by Kaltschmit et al. (1997).

Biofuel production has become a more important issue since the Biofuels Directive (EU Directive 2003/30/EC) came into force in May 2003. Member States are asked to set national indicative targets for 2005 and 2010 for the minimum proportion of biofuels and other renewable fuels in road fuels, against reference values of 2% for 2005 and 5.75% by 2010. Only biodiesel will be sufficiently developed in the UK to meet the 2005 requirement and would require a 45 to 108% increase in the area of a oilseed rape (Turley et al., 2004). The environmental impact of this expansion is unknown, but

Turley et al. (2004) conclude that there are unlikely to be any major environmental impacts unless spring sown break crops are replaced by winter oilseed rape. It would be desirable to undertake a study that analyses the impacts of oilseed rape using the same techniques used in **Submitted Publication 5.** This would allow a direct comparison with sugar beet. This could then be extended to a comparison of the environmental impact of biodiesel and bioethanol production from these two and other feedstocks.

This study provided a comprehensive assessment of the sugar beet crop in the UK using some of the most up-to-date techniques available. But there are some important topics that were not covered, for example the impact of field operations on soil. Such topics lack scientific understanding and an assessment framework, a common problem when dealing with issues related to soil protection (**Submitted Publication 6**).

3.7. Assessing risks to soils and the functions they perform

Soils perform a number of important functions that are critical to environmental sustainability (Arshad and Martin, 2002; Doran et al., 2002; Herrick, 2000 and Schloter et al., 2003). They are not only the primary medium for agricultural production but they influence many other environmental impacts as well. Consequently it is important to fully understand the processes involved and impacts on the functional ability of soils. **Submitted Publication 6** describes a prototype method developed to help prioritise soil protection issues. The method needed to identify relative risks to soil functions from different activities and identify the soil functions and properties at greatest risk. Knowledge about soils, their properties, processes and functional capabilities is patchy. Thus the method needed to find some way of explicitly highlighting where gaps and uncertainties exist and to reflect this in the assessment outputs. It needed to be able to capture knowledge ranging from detailed and documented scientific understanding to expert judgement and anecdotal information.

Given these requirements a method was designed based around the development of a knowledge base. This was structured to capture knowledge in a suitable format for risk assessment and assess confidence in the data and scientific understanding. This allowed any type of knowledge from precise scientific measurements to anecdotal information to be stored. Then when the knowledge base was interrogated and risks to soils derived, the quality and confidence of the information on which those risks are based can be presented simultaneously. Scoring and ranking techniques are used both to communicate the significance of the risks and the confidence in the risk assessment. Similar to p-EMA (**Submitted Publication 3**) the end user is presented with a summary of the risks and confidence that they can then drill down through to the raw data in the knowledge base if required.

One of most difficult problems in this project was extracting knowledge from soil experts in an appropriate format to construct the knowledge base. This was overcome by adapting the software to operate as a tool for constructing the soil change scenarios as well as a tool for interrogating the knowledge base. However, even when given this tool the experts had a limited time available for creating soil change scenarios. Consequently the soil change scenario format was only tested to a limited extent and would benefit from a more thorough test. A knock on effect from this problem was that the knowledge base that was created in the project was also limited so the interrogation facilities could only be tested on a small set of soil change scenarios. This was adequate for the purposes of the project, but the knowledge base structure and interrogation processes could do with a larger amount of scenarios to fully test it.

The technique developed and applied within this project provided a useful exploration of how qualitative information can be handled in environmental measurement and assessment. One thing this study also did, which was perhaps not tackled in **Submitted Publications 2-5**, was that it tried to characterise impacts to soil functions in terms of their significance. A scoring technique was developed based on the assumption that impacts that are rapidly occurring, large scale and hard to reverse are more significant than those that are slow to occur, small scale and easy to reverse. This allowed some prioritisation to occur during the interrogation process. There was also an attempt to identify any specific thresholds that had been crossed during any impacts. These related to critical thresholds in relation to specific soil properties and not necessarily impacts on soil functions, but it was a step in the right direction with regard to assessing the significance of effects and impacts.

The main emphasis of this work was on developing an interpretative framework to assess risks to soils, based on the numerous indicators and measurements available. In the past much of the work on soils has focused on developing indicators and measures of soil quality (Anderson, 2003; Arshad and Martin, 2002; Bindaraban et al., 2000; Griffiths et al., 2001; Hargreaves et al., 2003 and Schloter et al., 2003) rather than assessing risks and impacts. Consequently the work undertaken for this paper is a step in the right direction for improving our understanding of soils and impacts upon their functional ability, within the context of informing the policy creation process. Work of a similar nature to this has been undertaken in New Zealand (Lilburne et al., 2004 and Sparling and Schipper, 2004). The approach taken in the New Zealand study overlaps much of the work in **Submitted Publication 6** in terms of assessing impacts on soils and it also overlaps with the work in **Submitted Publication 7** in terms of using effect-damage relationships and targets.

3.8. Assessing the environmental impacts of agricultural policy

Determining the significance of effects and impacts in terms of environmental damage is perhaps one of the most difficult tasks in environmental assessment. Generally, we do not have any difficulties in characterising effects as negative or positive, e.g. we know it is desirable to reduce nitrate losses, releases of greenhouse gases and the toxic effects of pesticides. But often the severity or significance of the actual environmental damage being caused is not assessed. There are a number of techniques that attempt to address this issue. For example, economic valuation techniques aim to internalise the external environmental costs by attaching monetary values to them. This can be a valid approach and can help identify policy priorities, for example, the cost of removing nitrates and pesticides from drinking water supplies (Pretty et al., 2000). However, in other instances it is a more controversial technique, especially for items that tend to transcend conventional economic frameworks and monetary valuation, such as biodiversity and human health (Gregory and Slovic, 1997). Economic techniques also do not necessarily characterise actual impacts or damage. One approach that tries to do this is the distance to target method. This has been developed and used by a number of organisations (NOH, 1995, ENDS, 1994, Hammond et al., 1995 and Seppälä and Hämäläinen, 2001) particularly for Life Cycle Assessment (LCA). The method ranks impacts as being more important the further away an activity is from achieving desired targets. A change in an effect is converted to an index of damage based on an effect-damage relationship (or damage function). NOH (1995) use multiples of the target level to set the index and a standard sigmoid curve as a model in toxicology for the effect-damage relationship.

Submitted Publication 7 describes a prototype framework for a method in which the distance to target approach was adapted to assess the environmental impacts of agricultural policy. Assessing the impacts of a policy is inherently more difficult than other impact assessment scenarios due to the often indirect nature of a policy. For example, placing a tax on pesticides (ECOTEC et al., 1999) could influence pesticide use behaviour in numerous ways, whilst at the same time there are other influences such as retailer restrictions on pesticides, reviews revoking the use of pesticides and good practice promotions such as the Voluntary Initiative (CPA, 2004). Thus allocating an effect to a specific policy can be difficult. The method developed, SEAM, aimed to provide the Ministry of Agriculture, Fisheries and Food with information about the environmental impact of a policy. Areas of particular interest include environmental trade-offs, e.g. between ammonia emissions (DEFRA, 2002) and nitrate leaching (Silcock et al., 2004), with the desire to avoid conflict between policies. A scoring and ranking system was developed for communicating the significance of impacts, which utilises environmental targets and effect-damage relationships to convey the relative significance of the impacts of a policy. However, the level of uncertainty in the effect-damage relationships and targets were a significant issue that prevented the technique being developed into a practical tool for policy impact assessment. This was illustrated with the example of reducing the amount of fertiliser applied and its consequent impact on human health (Figures 3a, b, c and 4 in **Submitted Publication 7**). The relationships between the amount of N leached into groundwater, the amount of N in groundwater that ends up in drinking water and the amount of N in drinking water and its impact on human health are all very uncertain. Consequently in combination the uncertainty is compounded.

In an attempt to cope with the levels of uncertainty a confidence assessment system was also developed to capture the levels of uncertainty and communicate this to the policy maker. This was a useful technique for recording the quality of data and the scientific relationships used within the assessment. Many assessment techniques try to eliminate uncertainty and improve confidence by ensuring that the quality of the data used is high, this especially the case for LCA. However, they do not have systems in place to express any variations in data quality and consequent uncertainty in the results. So this respect the development of the confidence assessment system here was a novel advance. However, even with this confidence assessment system SEAM was still too cumbersome to be a viable as practical tool.

The key findings of the paper are not SEAM itself, but it's various components in terms of assessing the significance of impacts and capturing levels of confidence and uncertainty. In many respects the approach of correlating effects with levels of damage is correct, even more so if the target levels are based on some idea of what thresholds are sustainable. However, establishing relationships between effects and damage and determining sustainability thresholds is very difficult. So in many instances they simply do not exist. This is clearly an area for future research.

4.0. Conclusions and Future Directions

4.1. Discussion

This research has explored a range of tools from simple measures and indicators (**Submitted Publication 2**) to complex assessment techniques (**Submitted Publications 6 and 7**). All of these tools have had a common set of issues to tackle that were identified in the review (**Submitted Publication 1**), i.e. maintaining an holistic perspective, lack of data, uncertainty and confidence, masking of data and assessment findings and lack of scientific understanding. These have all been addressed by the work undertaken in this research.

The studies described have all had their own boundaries and individual objectives, which in some instances were quite narrow. However, as illustrated in **Submitted Publication 5**, it is possible to combine the techniques in order to obtain a more holistic picture. There is however further scope to develop a more holistic picture, perhaps by combining the techniques in **Submitted Publications 2-5**, with some of the emerging techniques in **Submitted Publications 6 and 7** to provide a better assessment of the significance of effects and impacts. Our level of scientific understanding also influences our holistic picture, as we have detailed knowledge and clear understanding of some aspects, but a vague and fuzzy understanding of others. We can also broaden our perspective to include techniques for assessing social and economic aspects alongside the environment, in order to achieve the balanced perspective required for making assessments of sustainability.

Lack of data is a common problem for all environmental assessments. It would be ideal to be able to measure and collect all the data and information we desire to make a thorough assessment, but this is not practical or cost-effective. Lack of measured data has been overcome in many instances through advances in modelling, such as p-EMA (**Submitted Publication 3**). Indicators (**Submitted Publication 2**) can also provide a means of overcoming instances when it is not possible to measure parameters directly. Expert judgement, such as that used in **Submitted Publication 6**, can also be used to fill gaps where there is a lack of data. This does, however, have implications for the uncertainty and confidence in the overall assessment, which is something that all studies have to address.

Confidence in the end results is a critical factor in any study. Uncertainty can arise at various points throughout a study from the collection of raw data, errors in modelling and calculations and aggregation of data and results. Often the levels of uncertainty and confidence are not expressed in the final results of a study. This makes the assumption that if there was a lack of confidence in assessment that the findings would not be presented to the end audience. However, as illustrated with the national indicators (**Submitted Publication 2**) the variation in the quality of the data and the consequent trend they depict is highly variable, but this was not expressed when the 35 indicators are presented alongside each other. Variability in data quality was tackled in **Submitted Publications 3, 6 and 7** and confidence and uncertainty was explicitly assessed and communicated in **Submitted Publications 6 and 7**. Uncertainty and confidence is addressed in most scientific studies but it often not addressed when communicating results to end audiences. This is something that has been attempted in this research, albeit with limited success. This is an area that still needs further development in the future.

Related to this is the problem of aggregating large amounts of data that can lead to important detail and findings being masked and uncertainty. The indicators (**Submitted Publication 2**) are a good example, where the national set provided little detail on the variation of the indicators by location and farm type. When these were broken down, significant variations were revealed that showed how the values did vary by geographical location and farm type. In the other studies (**Submitted Publications 3 to 7**) the data were presented in a transparent way and drilling down through the various levels of aggregation could reveal the detail. The p-EMA software (**Submitted Publication 3**) is a good example where this can be easily done, not only to show the full depth of the data, but also the quality of the data. Advances in information technology mean that handling of large data sets and ability to interrogate them and drill down through the information is a more practical and feasible option. Integration with Geographical Information System (GIS) tools could also greatly advance such an approach, perhaps applying risk assessment techniques spatially.

Finally, the level of scientific understanding is an ultimate limitation for all studies and can contribute to uncertainty. There is little that can be done in an assessment when there is a lack of scientific understanding. However, it is important that it is identified and highlighted as a need for future research. In particular for environmental assessment, as revealed in **Submitted Publications 6 and 7**, the level of scientific understanding in effect-damage relationships and targets and thresholds is an area that needs further research and development. There are also particular effect/impact areas that require further work, such indirect effects on human health and biodiversity. These are two big areas where improvements in our science and assessment techniques are still required.

To conclude, we have a range of different tools available to help us construct a picture of the environmental impact of agriculture. The studies described above have all had their own individual objectives. However, in combination they are starting to construct a wider more holistic picture. There are undoubtedly still fuzzy areas that are not fully understood and in other places there are complete gaps in knowledge and understanding, such as impacts on biodiversity and human health. However, the picture we have now is certainly better than it was only 10 years ago and there is no reason why it shouldn't improve as our knowledge and understanding evolves and as our measurement and assessment tools improve. However, it will be important to understand how we use the tools we have available to construct the same picture for different audiences, and avoid any conflicting images between policy and farm level. One solution may be where the more complex tools and techniques (used locally at the farm level) feed data to the tools, techniques and indicators at the policy level. This integrated approach is entirely feasible with recent advances in information technology and may not be that far way. There are initiatives in place such as DEFRA's Whole Farm Approach, the Environment Agency's Environmental Management System for Farms (EMSF) and the Land Management Information System (LaMIS) project, which in combination will greatly increase the amount of data collected at the farm level and the assessments made. This data can be fed upward to regulators and the government to make risk assessments and judgements on the activities taking place on farm. Action can then be taken either in the form of policies, enforcement or provision of guidance on a targeted basis to farms that have been identified as high risk. Such an approach clearly demonstrates that there are still many more advances that can be made in the future to improve our tools and techniques for environmental assessment, many of which have been outlined in this research.

4.2. Summary

In summary the main findings and conclusions of this research are:

- Combining techniques (**Submitted Publications 2-5**) can provide a more holistic picture and this could be further improved by incorporating emerging techniques (**Submitted Publications 6 and 7**) and broadening the scope to encompass social and economic assessments.
- Lack of data can be overcome using modelling techniques (**Submitted Publication 3**) or alternative measures such as indicators (**Submitted Publication 2**) and expert judgement (**Submitted Publication 6**).
- Confidence and uncertainty is a common problem in environmental assessments, caused by data quality problems, levels of scientific understanding and aggregation. These have been tackled in this research (**Submitted Publications 2, 3, 6 and 7**) with limited success.
- The level of scientific understanding was specifically tackled (**Submitted Publications 6 and 7**) in relation to effect-damage relationships and target and threshold levels of environmental damage. This is an area that still needs further research, often at quite a fundamental level, particularly for issues such as indirect effects on human health and biodiversity.
- Finally, the picture we have today is better than it was 10 years ago. However, there are still areas that are fuzzy and not fully understood and these should be the areas of focus for future research. It will also be important to obtain a common picture from the farm to policy perspective, so we need to ensure that the different techniques used at different levels do not produce contradictory pictures. Indeed they should draw upon the same data sources and ideally integrate with each other. This is feasible with the information technology with have available.

References

Anderson T. H. (2003) Microbial eco-physiological indicators to asses soil quality. *Agriculture, Ecosystems and Environment* **98**, 285–293

Andersson, K., Ohlsson, T and Olsson, P. (1994) Life-Cycle Assessment (LCA) of food products and productions systems. *Trends in Food Science and Technology* **5**:**5**, 134-138

Arshad, M. A. and Martin, S. (2002) Identifying critical limits for soil quality indicators in agro-ecosystems *Agriculture, Ecosystems and Environment* **88**, 153–160

Bailey, A. P., Basford, W. D., Penlington, N., Park, J. R., Keatinge, J. D. H., Rehman, T., Tranter, R. B. and Yates, C. M. (2003) A comparison of energy use in conventional and integrated arable farming systems in the UK. *Agriculture, Ecosystems and Environment* **97**, 241–253

Barrett, J, and Scott, A. (2001) The Ecological Footprint: A Metric for Corporate Sustainability. *Corporate Environmental Strategy* **8**, 316-325

Barrett, J. and Simmons, C. (2003) *An Ecological Footprint of the UK: Providing a Tool to Measure the Sustainability of Local Authorities.* Stockholm Environment Institute and Best Foot Forward Ltd

Bennett, R., Phipps, R., Strange, A., and Grey, P. (2004) Environmental and human health impacts of growing genetically modified herbicide-tolerant sugar beet: a life-cycle assessment. *Plant Biotechnology Journal* **2**, 273–278

Bicknell, K. B., Ball, R. J., Cullen, R. and Bigsby, H. R. (1998) New methodology for the ecological footprint with an application to the New Zealand economy. *Ecological Economics* **27**, 149-160

Bindraban, P. S., Stoorvogel, J. J., Jansen, D. M., Vlaming, J. and Groot, J. J. R. (2000) 103–112 Land quality indicators for sustainable land management: proposed method for yield gap and soil nutrient balance *Agriculture, Ecosystems and Environment* **81**, 103–112

Borrero, M. A. V., Pereira; J. T. V. and Miranda, E. E. (2003) An environmental management method for sugar cane alcohol production in Brazil. *Biomass and Bioenergy* **25**, 287-299

Brown C. D., Hart, A., Lewis, K. A. and Dubus I. G. (2003) p-EMA (I): simulating the environmental fate of pesticides for a farm-level risk assessment system. *Agronomie*. **23**, 67-74

Carson, R. (1962) *Silent Spring*. Penguin Books, London

Cheung, S. T. S. (1994) *A Life Cycle Assessment Approach to Used Tyre Management*. MSc Dissertation. School of natural and Environmental Sciences, Coventry University.

Council Directive 91/156/EEC 18 March 1991 amending Directive 75/442/EEC on waste *Official Journal of the European Union* L 078 , 26/03/1991 P. 0032 - 0037

Council Directive 91/414/EEC concerning the placing of plant protection products on the market. *Official Journal of the European Commission*, No. L230/1, 19/08/1991.

Council Regulation EC 1782/2003 of 29 September 2003 establishing common rules for direct support schemes under the common agricultural policy and establishing certain support schemes for farmers and amending Regulations (EEC) No 2019/93, (EC)No 1452/2001,(EC)No 1453/2001,(EC)No 1454/2001,(EC)1868/94,(EC)No 1251/1999,(EC) No 1254/1999,(EC)No 1673/2000,(EEC)No 2358/71 and (EC)No 2529/2001. *Official Journal of the European Union* L 270/1 21.10.2003

Council Regulation EC/1260/2001 *on the common organisation of the markets in the sugar sector*. Official Journal of the European Communities. 30 June 2001 (L 178/1-45)

CPA (2004) *Third Annual Report of the Voluntary Initiative Steering Group*. Crop Protection Association (CPA). 2004

de Carvalho Macedo, I. (1996) Greenhouse gas emissions and energy balances in bio-ethanol production and utilization in Brazil (1996). *Biomass and Bioenergy* **14**, 77-81

DEFRA (2002) *Ammonia in the UK*. Department for Environment, Food and Rural Affairs, 2002

DEFRA (2004) Quality of Life Counts. Indicators for a strategy for sustainable development for the United Kingdom. 2004 Update. Updating the baseline assessments made in 1999. Department for Environment, Food and Rural Affairs. March 2004

Directive 2000/60/EC of The European Parliament and of The Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Union* L 327/1 22.12.2000

Dodgson, J., Spackman, M., Pearman, A. and Phillips, L. (2000). *Multi-Criteria Analysis: A Manual*. London, Office of the Deputy Prime Minister.

DOE (1995) *A Guide to Risk Assessment and Risk Management for Environmental Protection.* Department of the Environment, HMSO. ISBN 0 11 753091 3

Doran, J. W., Stamatiadis, S. I. and Haberern, J. (2002) Soil health as an indicator of sustainable management. *Agriculture, Ecosystems and Environment* **88**, 107–110

ECOTEC, University of Hertfordshire, Central Science Laboratory and the University of Newcastle upon Tyne (1999) *Design of a Tax or Charge Scheme for Pesticides.* Published as a Government consultation paper by the Department of the Environment, Transport and the Regions (DETR). ISBN 1 851121 60 9

EEA (1999) *Environmental indicators: Typology and review.* European Environment Agency, Copenhagen.

EFRAC (2004) *Reform of the Sugar Regime: Government Reply to the Committee's Report. Sixteenth Special Report*. Environment, Food and Rural Affairs Committee (EFRAC), House of Commons. HC 1129. 20 October 2004. London: The Stationery Office Limited

ENDS (1994) The elusive consensus on life-cycle assessment. *ENDS Report* **231**, 20-22

Environment Agency (2004) *Pesticides 2003*. Annual Report of the Environment Agency's pesticide monitoring programme.

Environment Agency (2000) *Introducing Environmental Risk Assessment*. National Centre for Risk Analysis and Options Appraisal, Environment Agency.

EU Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 *on the promotion of the use of biofuels or other renewable fuels for transport*. Official Journal of the European Union L 123/42 17 May 2003

Firbank, L.G., Heard, M.S., Woiwod, I.P., Hawes, C., Haughton, A.J., Champion, G.T., Scott, R.J., Hill, M.O., Dewar, A.M., Squire, G.R., May, M.J., Brooks, D.R., Bohan, D.A., Daniels, R.E., Osborne, J.L., Roy, D.B., Black, H.I.J., Rothery, P. and Perry, J.N. (2003) An introduction to the Farm-Scale Evaluations of genetically modified herbicide-tolerant crops. *Journal of Applied Ecology* **40**, 2–16

Flessa, H., Ruser, R., Dörsch, P., Kamp, T., Jimenez, M. A., Munch, J. C. and Beese, F. (2002) Integrated evaluation of greenhouse gas emissions (CO_2, CH_4, N_2O) from two farming systems in southern Germany *Agriculture, Ecosystems and Environment* **91**, 175–189

Forestry Commission (2002) *UK Indicators of Sustainable Forestry*. Economics and Statistics Unit Forestry Commission October 2002. ISBN 0-7559-1025-7

Green, E., Short, S. and Taylor, M. (2000) *Guidelines for Environmental Risk Assessment and Management*. Prepared for the Department of the Environment, Transport and the Regions (DETR).

Gregory, R. and Slovic, P. (1997) A constructive approach to environmental valuation *Ecological Economics* **21**:175-181

Griffiths, B. S., Bonkowski, M., Roy, J. and Ritz, K. (2001) Functional stability, substrate utilisation and biological indicators of soils following environmental impacts. *Applied Soil Ecology* **16**, 49–61

Haberl, H., Erb, K. H., Krausmann, F. (2001) How to calculate and interpret ecological footprints for long periods of time: the case of Austria 1926–1995 *Ecological Economics* **38**, 25–45

Haberl, H., Wackernagel, M., Krausmann, F., Erb, K. H. and Monfreda, C. (2004) Ecological footprints and human appropriation of net primary production: a comparison. *Land Use Policy* **21**, 279–288

Halberg, N., Verschuur, G. and Goodlass, G. (2004) Farm level environmental indicators; are they useful? An overview of green accounting systems for European farms *Agriculture, Ecosystems and Environment*. In Press

Hammond, A., Adriaanse, A., Rodenburg, E., Bryant, D. and Woodward, R. (1995) *Environmental Indicators: A Systematic Approach to Measuring and Reporting on Environmental Policy Performance in the Context of Sustainable Development.* World Resources Institute.

Hargreaves, P. R., Brookes, P. C., Ross, G. J. S., Poulton, P. R. (2003) Evaluating soil microbial biomass carbon as an indicator of long-term environmental change. *Soil Biology and Biochemistry* **35**, 401–407

Hart, A., Lewis, K. A., Brown C. D. and **Tzilivakis**, J. (2003) p-EMA (II): simulating the environmental risk of pesticides for a farm-level risk assessment system. *Agronomie*. **23**, 75-84

Herrick, J. E. (2000) Soil quality: an indicator of sustainable land management*? Applied Soil Ecology* **15**, 75–83

Hueting, R. and Reijnders, L. (2004) Broad sustainability contra sustainability: the proper construction of sustainability indicators. *Ecological Economics* **50**, 249– 260

Hülsbergen, K. J., Kalk, W. D. (2001) Energy balances in different agricultural systems - can they be improved? *The International Fertiliser Society Proceedings* No **476**

Hunsaker, C. T., Carpenter, D. E. and Messer, J. (1990) Ecological Indicators for regional monitoring. *Ecology Society of America Bulletin* **71**, 165-172

Johnson, C. J. (1993) *A Life Cycle Assessment of Incinerating or Recycling Waste Paper*. MSc Dissertation. Centre for Environmental Technology, Imperial College of Science, Technology and Medicine

Kaltschmitt, M., Reinhardt, G. A. and Stelzer, T. (1997) Life Cycle Analysis of Biofuels Under Different Environmental Aspects. *Biomass and Bioenergy* **12:2**, 121-134

Kirkman, H (2004) *DEFRA Consultation: Review of the EU Sugar Sector*. Policy Statement, National Farmers Union, 16 January 2004

Leake, A. R. (2000) Climate change, farming systems and soils. *Aspects of Applied Biology* **62**, 253-259

Lewis, K. A., Brown, C. D., Hart, A. and **Tzilivakis**, J. (2003) p-EMA (III): Evaluating a farm-level risk assessment system for agricultural pesticides. *Agronomie*. **23**, 85-96

Lilburne, L., Sparling, G. and Schipper, L. (2004) Soil quality monitoring in New Zealand: development of an interpretative framework. *Agriculture, Ecosystems and Environment* **104**, 535–544

MAFF (Ministry of Agriculture Fisheries and Food) (2000) *Towards Sustainable Agriculture: A Pilot Set of Indicators*. DEFRA Publications: London. PB4583.

Margni, M., Rossier, D., Crettaz, P. and Jolliet, O. (2002) Life cycle impact assessment of pesticides on human health and ecosystems. *Agriculture, Ecosystems and Environment* **93**, 379–392

McDonald, G. W. and Patterson, M. G. (2004) Ecological Footprints and interdependencies of New Zealand regions. *Ecological Economics* **50**, 49-67

Monfreda, C., Wackernagel, M. and Deumling, D. (2004) Establishing national natural capital accounts based on detailed Ecological Footprint and biological capacity assessments. *Land Use Policy* **21**, 231-246

NOH (The Dutch National Reuse of Waste Research Programme) (1995) *The Eco-indicator 95. Final Report.* Report produced under the responsibility of the Netherlands agency for energy and the environment (Novem), and, the National Institute of Public Health and Environmental Protection (RIVM).

OECD (2004) *OECD Key Environmental Indicators 2004*. Organisation for Economic Co-operation and Development, Environment Directorate, Paris, France

OECD (1994) *Environmental Indicators*. OECD Core Set. Organisation for Economic Co-operation and Development, Paris, France

Ogilvy S. E., Turley D. B., Cook S. C., Fisher N. M., Holland J., Prew R. D. and Spink J., (1994) Integrated farming – putting together systems for farm use, *Aspects of Applied Biology* **40**, 53–60.

Perry, J., Clark, S. and Rothery, P. (2004) Research Needs on the Design, Analysis and Statistical Power of Studies of the Effects of Agricultural Practices on Biodiversity. In Young, J., Bolger, T., Kull, T., Tinch, R., Scally, L. and Watt, A.D. (Eds) (2004) *Sustaining livelihoods and Biodiversity- attaining the 2010 target in the European Biodiversity Strategy*, report of an electronic conference for the European Platform for Biodiversity Research Strategy. pp 36

Pervanchon, F., Bockstaller, C. and Girardin, P. (2002) Assessment of energy use in arable farming systems by means of an agro-ecological indicator: the energy indicator. *Agricultural Systems* **72**, 149–172

Pretty, J. N., Brett, C., Gee, D., Hine, R. E., Mason, C. F., Morison, J. I. L., Raven, H., Rayment, M. D. and van der Bijl, G. (2000) An assessment of the total external costs of UK agriculture, *Agricultural Systems* **65**(2):113-136

RBU and RAC (2004) *Economic, Social and Environmental Implications of EU Sugar Regime Reform*. Final Report Rural Business Unit (RBU) University of Cambridge and the Royal Agricultural College (RAC). September 2004

RCEP (2004) Royal Commission Study on Pesticides and Bystander Exposure. Royal Commission on Environmental Pollution. Due to report in May 2005

Robinson, G. (1996) Environmental Rating - Concepts and Approach. *Environmental Assessment* December 1996, 14-16

Reus, R., Leendertse, P., Bockstaller, C., Fomsgaard, I., Gutsche, V., Lewis, K., Nilsson, C., Pussemier, L., Trevisan, M., van der Werf, H., Alfarroba, F., Blümel, S., Isart, J., McGrath, D. and Seppälä, T. (2002) Comparison and evaluation of eight pesticide environmental risk indicators developed in Europe and recommendations for future use *Agriculture, Ecosystems and Environment* **90**, 177–187

Reus, J., Leendertse, P., Bockstaller, C., Fomsgaard, I., Gutsche, V., Lewis, K., Nilsson, C., Pussemier, L., Trevisan, M., Van der Werf, H., Alfarroba, F., Blümel, S., Isart, J., McGrath, D., Seppälä, T. (1999) *Comparing environmental risk indicators for pesticides - Results of the European CAPER project*. Centre for Agriculture and Environment, Utrecht. July 1999. CLM 426-1999

Rigby, D., Woodhouse, P., Young, T. and Burton, M. (2001) Constructing a farm level indicator of sustainable agricultural practice. *Ecological Economics* **39**, 463–478

Scholter, M., Dilly, O. and Munch, J.C. (2003) Indicators for evaluating soil quality. *Agriculture, Ecosystems and Environment* **98**, 255-262

Seppälä, J. and Hämäläinen, R. P. (2001) On the Meaning of the Distance-to-Target Weighting Method and Normalisation in Life Cycle Impact Assessment. *International Journal of Life Cycle Assessment* **6**(4):211-218

Silcock, P. Swales, V., Smith, G. and Sealy, K. (2004) *Impacts of CAP Reform Agreement on Diffuse Water Pollution from Agriculture*. Report prepared for the Department for Environment, Food and Rural Affairs (DEFRA), April 2004 by GFA-RACE Partners Limited and The Royal Agricultural College

Skinner, J. A., Lewis, K. A., Bardon, K. S., Tucker, P., Catt, J. A. and Chambers, B. J. (1997) Overview of the Environmental Impact of Agriculture in the UK. *Journal of Environmental Management* **50**, 111-128

Smith, J. U., Bradbury, N. J. and Addiscott, T. M., (1996) SUNDIAL: A PC-based system for simulating nitrogen dynamics in arable land. *Agronomy Journal* **88**, 38-43

Sparling, G. and Schipper, L. (2004) Soil quality monitoring in New Zealand: trends and issues arising from a broad-scale survey *Agriculture, Ecosystems and Environment* **104**, 545–552

Sustain (2001) *Eating Oil - Food in a Changing Climate*. A Sustain/Elm Farm Research Centre Report. December 2001

Suter, G. W. (1990) Endpoints for regional ecological risk assessments. *Environmental Management* **14**, 9-23

Turley, D., Bullard, M. and Martin, D. (2003) Liquid biofuels - industry support, cost of carbon savings and agricultural implications. Prepared for Defra Organic Farming and Industrial Crops Division. August 2003

Tzilivakis, J. and Lewis, K. A. (1999) Environmental Management for Agriculture (EMA) and Sustainable Agriculture. In Schiefer, G. et al. (Eds.) *Perspectives of Modern Information and Communication Systems in Agriculture, Food Production and Environmental Control* (Volume A) Proceedings of the Second European Conference of the European Federation for Information Technology in Agriculture, Food and the Environment. September 27-30, 1999, Bonn, Germany. pp 175-185 van den Bergh, J. C. J. M. and Verbruggen (1999) Spatial sustainability, trade and indicators: an evaluation of the ‘ecological footprint’. Ecological Economics 29, 61-72

van der Werf, H. M. G. and Petit, J. (2002) Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods *Agriculture, Ecosystems and Environment* **93**,131–145

Wackernagel, M., Monfreda, C., Schulz, N. B., Erb, K. H., Haberl, H. and Krausmann, F. (2004) Calculating national and global ecological footprint time series: resolving conceptual challenges. *Land Use Policy* **21**, 271-278

Wackernagel, M. Onisto, L., Bello, P., Linares, A. C., Falfán, I. S. L, García, J. M. Guerrero, A. I. S. and Guerrero, G. S. (1999) National natural capital accounting with the ecological footprint concept. *Ecological Economics* **29**, 375-390

Wackernagel, M. and Rees, W. E. (1996) *Our Ecological Footprint: Reducing Human Impact on the Earth*. New Society Publishers, Gabriola Island, BC.

WWF (2004a) *Living Planet Report 2004*. WWF, UNEP World Conservation Monitoring Centre and the Global Footprint Network. Cambridge, United Kingdom. ISBN: 2-88085-265-X. October 2004

WWF (2004b) *Sugar and the Environment. Encouraging Better Management Practices in Sugar Production and Processing*. WWF, 22 November 2004.

WWF (2004c) *What is the Ecological Footprint?* WWF Briefing. July 2004

Appendix A. Co-author statement

1. Newbold, M. J., Lewis, K. A., **Tzilivakis**, J., Finch, J, Kähö, T. M., Skinner, J. A. and Bardon, K. (1997) Options for informal environmental management: the agricultural industry highlighted. *Eco-Management and Auditing* **4**, 22-27
   The candidate was responsible for: Planning: 15%, Execution: 30%, Analysis: 30% and Preparation: 15%

2. **Tzilivakis**, J. and Lewis K.A. (2004) The development and use of farm level indicators in England. *Sustainable Development* **12**, 107-120
   The candidate was responsible for: Planning: 80%, Execution: 70%, Analysis: 85% and Preparation: 50%

3. **Tzilivakis**, J., Turley, D. B., Ogilvy, S. E., Lewis, K. A. and Lawson, K. (2004) Assessing the environmental impact of crop protection strategies for integrated farming systems. *Agronomie* **24**, 67-76
   The candidate was responsible for: Planning: 30%, Execution: 65%, Analysis: 65% and Preparation: 15%

4. **Tzilivakis**, J., Jaggard, K., Lewis, K. A., May, M. and Warner, D. J. (In press) Assessment of the energy inputs and greenhouse gas emissions in sugar beet (Beta vulgaris) production in the UK. *Agricultural Systems* In press (available online at: www.sciencedirect.com)
   The candidate was responsible for: Planning: 60%, Execution: 70%, Analysis: 70% and Preparation: 25%

5. **Tzilivakis**, J., Jaggard, K., Lewis, K. A., May, M. and Warner, D. J. (2005) Environmental Impact and Economic Assessment for UK Sugar Beet Production Systems. *Agriculture, Ecosystems and Environment* **107**, 341-358
   The candidate was responsible for: Planning: 90%, Execution: 90%, Analysis: 90% and Preparation: 100%

6. **Tzilivakis**, J., Lewis K. A. and Williamson, A. R. (2005) A prototype framework for assessing risks to soil functions. *EIA Review* **25**, 181-195
   The candidate was responsible for: Planning: 90%, Execution: 90%, Analysis: 90% and Preparation: 100%

7. **Tzilivakis**, J., Broom, C., Lewis, K. A., Tucker, P., Drummond, C. and Cook, R. (1999) A Strategic Environmental Assessment Method for Agricultural Policy in the UK. *Land Use Policy* **16**, 223-234
   The candidate was responsible for: Planning: 85%, Execution: 85%, Analysis: 85% and Preparation: 100%

Candidate: ………………………… Date: ……………………

Senior Line Manager: ………………………… Date: ……………………

Appendix B. Other related publications

Hart, A., Lewis, K. A., Brown C. D. and **Tzilivakis**, J. (2003) p-EMA (II): simulating the environmental risk of pesticides for a farm-level risk assessment system. *Agronomie* **23**, 75-84

Jaggard, K., **Tzilivakis,** J., Warner, D. J. and Lewis, K. A. (2004) Beet and the Environment. *British Sugar Beet Review* **72:2**, 34-37

Lewis, K. A., Brown, C. D., Hart, A. and **Tzilivakis**, J. (2003) p-EMA (III): Evaluating a farm-level risk assessment system for agricultural pesticides. *Agronomie* **23**, 85-96

Lewis, K. A., Newbold, M. J. and **Tzilivakis**, J. (1999) Developing an emissions inventory from farm data. *Journal of Environmental Management* **55**, 183-197

Lewis, K. A. and **Tzilivakis**, J. (1998) Evaluating a Technique Used to Measure Environmental Performance within Agriculture - Case studies. *Eco-Management and Auditing* **5:3**, 126-135

Lewis, K. A. and **Tzilivakis,** J. (2000) The role of the EMA software in integrated crop management and its commercial uptake. *Pest Management Science* **56**, 969-973

Tzilivakis, J. and Lewis, K. A. (1999) Environmental Management for Agriculture (EMA) and Sustainable Agriculture. In Schiefer, G. et al. (Eds.) *Perspectives of Modern Information and Communication Systems in Agriculture, Food Production and Environmental Control* (Volume A) Proceedings of the Second European Conference of the European Federation for Information Technology in Agriculture, Food and the Environment. September 27-30, 1999, Bonn, Germany. pp 175-185

Appendix C. Submitted Publications

Appendix D. Additional Publications