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The Use of Emergy Analysis for Measuring the Environmental Costs and Benefits of Agriculture Practices in Scotland

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ABSTRACT

Arable systems have to not only provide food for the masses, but they now have to be multi-functional. Thus they need to be managed to preserve the environment, satisfy social preference and provide a living for farmers, which may be conflicting objectives. Because it has the benefit of a common currency, emergy accounting has, therefore been used to assess the economic and environmental 'health' of the system. Currently, the emergy evaluation focuses on the impact of farm management practices on crop production at the field level and includes data on climatic inputs, such as sunlight and rainfall, and purchased inputs, such as fertilizers, labour and machinery. There is a need to understand how crop management practices may be developed and used to optimise the management of these components, particularly those reducing or reversing adverse environmental impacts whilst maintaining economic sustainability. Early results have shown that for Scottish agriculture spring barley and spring oats demonstrate the highest sustainability value. Therefore, these crops can be seen as utilizing renewable resources to their best effect and not exerting pressure on the agricultural environment. This result is very much influenced by the level of additional purchased inputs to the system (fertilisers and machinery). The addition of factors such as labour, soil type, and socio-economic factors related to the costs (£) of inputs will help to build a more robust picture of agriculture in Scotland.

INTRODUCTION

The sustainability of agricultural systems must be quantified to select those that can best meet the challenge of supplying food, materials, energy and environmental services to a growing population in a world with finite environmental and energy resources. Such evaluations should identify the agricultural systems with greater (crop) yields relative to their resource use and the fraction of resource use that is supplied from renewable resources. This will allow a reversal of a trend through the last century that saw greater yields in industrialised nations become more dependent on the use of non-renewable resources (Tiley and Martin, 2006).

Agricultural systems depend on inputs from both nature and the human economy; this makes determining agricultural sustainability problematic. Typically, high quality, non-renewable energies from the human economy are utilised to capture and concentrate lower quality, more abundant renewable energies provided by nature. Intensive agricultural methods rely more on resources purchased from the economy, while less intensive and indigenous methods typically rely more on natural inputs (Tiley and Martin, 2006). Most types of agriculture depend on a combination of natural and economic inputs. It is therefore necessary to account for both in equivalent terms when comparing the resource use of agricultural systems.

The main function of arable/grass farmland over the past 200 years has been to provide staple diets for large masses of people in the western world, which has been achieved (Evans, 1993). However, this has had consequences on the wider environment. The system now has to be multi-functional and therefore, agricultural land has to be managed to preserve its integrity, to satisfy social preferences, to provide a living for farmers, to be economically viable, and to be amenable to global shifts in climate. Whatever the shape of farming, the central biological mechanisms and properties should not be compromised and it is essential that a balance must be kept between the offtake and the essential biodiversity that keeps the system running.

It can be hypothesised that the right balance of biological organisms (flora and fauna) in the arable system can be attained over cropping sequences and across a landscape, so as to enable the system to satisfy economic, aesthetic and essential ecosystem function at the same time. This research will contribute to the design and testing of cropping systems for the climates and landscapes of Scotland (conventional and organic) to help give recommendations for resource use and improve crop yields.

Arable/grass landscapes in Scotland consist of cropped fields, their margins and boundaries, the vegetated areas outside fields and the land covered by infrastructure. The systems are potentially highly biodiverse and all parts of the landscape depend on a wide range of biological organisms for their proper functioning. Cropping in these fields is enhanced by sound management of soil, microbes and choice of plants. The main aim of this research is to quantify the existing balance of resources in cropping systems in Scotland, and define what the balance should be over space and time to enable the systems to remain resilient; that is, to be able to recover from or adapt to change. Our focus is on the cropped fields, although developments in the research could consider the marginal effects to the land. Resilience is a principle feature that would ensure these systems have a future in the foreseeable social, climatic and economic conditions.

This research aims not to seek one particular system that will satisfy current demands, but rather define the physical, biological and economic principles that should be the common basis of any or all future cropping systems in the climate and landscape of Scotland. This research will lay down methods and criteria for designing and testing new systems and will initiate on-farm experiments run jointly with stakeholders. While the work is applied to one country, the principles and methods outlined could be applied for any combination of social, economic and environmental conditions. Some examples of the types of beneficiaries from this research include policy makers, environmental bodies, scientific community, farmers and the general society/public.

The objective of the research is to understand and define quantitatively the social, economic and environmental components that influence arable land use systems. Hence, there is a need to understand how crop management practices may be developed and used to optimise the management of these components, particularly those reducing or reversing adverse environmental impacts whilst maintaining economic sustainability. Models will be produced that will explore how plant factors such as the crop variety and agronomic practices (such as fertiliser and labour application) influence biophysical, economic and aesthetic properties of the landscape. A modelling framework that aims to combine biophysical and socio-economic aspects of production ecology will be applied to add focus to the research and used to answer the research aims and objectives. The objective of the modelling framework proposed is that it can assess the economic and environmental 'health' of the system. In order to compare all aspects of the health of the system, including all inputs and outputs, a common currency will be used. This approach can be achieved by applying emergy evaluation.

Emergy accounting is a method for measuring both natural and human-made processes, including the environmental costs and benefits of agricultural practice. It overcomes the inability of many existing approaches to adequately consider the contribution of ecological processes to human progress and wealth. Emergy provides a bridge that connects economic and ecological systems and provides a more holistic alternative to many existing methods for environmentally conscious decision making. Scientists and consumers are becoming more interested and concerned in the environmental impacts of agricultural practices. Sustainability of crop production has to be given high priority when global biomass resources are limited. Emergy evaluation takes into account all inputs involved in a production system (i.e. renewable and non-renewable, local and imported) and transforms them into a common measure of direct and indirect solar energy requirement.

System models will be used to show which states, from among a large number of states, are best likely to meet the criteria for health and resilience of the ecosystem. The research will lead to a series of recommendation for improved agricultural management. The research proposed will define cropping systems within a wide continuum that (i) can continue in the long-term as healthy production systems in the face of external change; (ii) cause a minimum of environmental damage consistent with their productivity, and (iii) are adaptable enough to be used for different purposes at different times.

MATERIALS AND METHODS

This research will follow the general methodology for emergy accounting, which is a “top-down” systems approach (Ulgiati and Brown, 2000) that follows the principles of environmental accounting set out by Odum (1996). The methodology for emergy accounting begins with the construction of a systems diagram (Figure 1) to define the boundary, identify resource inputs, and conceptualise relationships among components, inputs and outputs. The emergy evaluation table is constructed directly from the systems diagram using inflows and outflows crossing the system boundary as row headings. The annual amount of flow of each input and output is first quantified in physical units (i.e. joules, grams, dollars). Then the annual solar emergy of each flow is estimated by multiplying each physical quantity by the appropriate emergy per unit factor, solar transformity, specific solar transformity, or the solar-to-money ratio, respectively. The flows are aggregated into categories of renewable resources (i.e. used resources at rates lesser than natural replenishment), non-renewable resources (i.e. used resources at rates bigger than natural replenishment), non-indigenous purchased resources (i.e. paid for and bought from outside the system), and exports (or yield).

Typically, renewable resources driving agricultural systems include sunlight, wind and rain. Since the ultimate source of these energies is the same, care must be taken not to double count their contribution of solar emergy. Non-renewable resources often include soil, groundwater, forest biomass and any other environmental resource that is being consumed at a rate faster than its natural formation cycle. Examples of purchased resources include fuel, fertilizer, irrigation water, chemicals, machinery, and labour. These aggregate categories serve as the basis for developing indices. These indices, which relate economic and environmental flows, are used to quantify investment intensity, net yield, environmental loading, and sustainability. The utility of a particular index depends on the specific goal or question of concern (Tiley and Martin, 2006).

For agriculture, it can be said that sustainability is considered to be a function of the emergy yielded by the process to the surrounding economy, the degree to which the process relies on renewable emergy flows, and the overall load the process places on the environment (Brown and Ulgiati, 1997). The main indices used to determine the sustainability of agriculture are the Emergy Yield Ratio (EYR) and the Environmental Load Ratio (ELR); which, when combined in the Sustainability Index (SI), give a general measure of ecological sustainability.

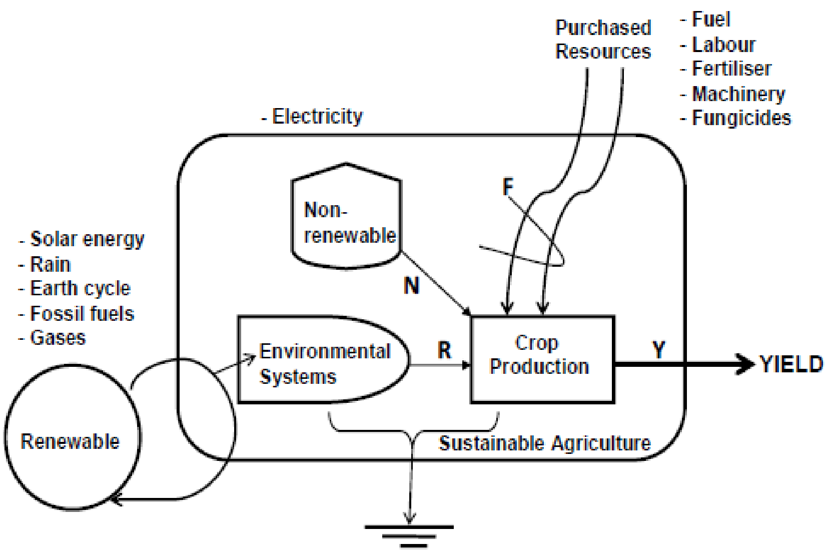

Figure 1: *Simple systems diagram for Scottish agriculture (field scale) highlighting the resources of interest. (R = renewable resources, N = Non-renewable resources, F = Purchased resources, Y = yield in relation to total emergy of the system).*

For the collection of data for the use in the analyses, field experiments have been set up. The experiments involved stratified on-farm sampling across farm types in Scotland. Data has been collected for approximately 50 paired fields that illustrate a cereal crop and a break crop. The information collected includes management data related to agricultural management techniques, socio-economic data that covers costs related to management techniques and the prices attainable for crops, crop yield, and details that describe the land areas within and outside the cropping area. Climatic data for this research has been obtained from alternative sources such as MET databases (http://www.metoffice.gov.uk) and other sources available to The Scottish Agricultural College. Emergy unit values (or emergy intensity values) are being extrapolated from previous research (Ulgiati *et al.*, 1994; Ulgiati and Brown, 1998; Haden, 2003) carried out in Europe to be relevant to Scottish agriculture.

RESULTS

Early results have shown that for Scottish agriculture spring barley, spring oats and vegetables demonstrate the highest sustainability value (Table 1). They are less reliant on purchased inputs and exerting less pressure on the agricultural environment than winter oilseed rape and winter wheat. This result is very much influenced by the level of additional purchased inputs to the system such as fertilizer application and machinery used. Data specific to the fields in Scotland has been collected for the purchased resources. The addition of factors such as labour, soil type, and socio-economic factors related to the costs (£) of inputs will help to build a more robust picture of agriculture in Scotland.

Additional tables related to these calculations detailing raw data, transformity valuations and calculation of the indices for these fields taken from the study are illustrated in Appendix 1.

DISCUSSION

The interface of environment and human society is often in the marketplace where resources are exploited and sold. During this process the environment will sustain some transformation that may or may not lead to long term stability. As the population expands, it is important that humans consider the long term environmental consequences of their economic decisions (Ulgiati et al., 1994). This includes decisions related to resource use in agriculture. Many sustainability assessments consider balances of energy and material flows without qualifying to what extent the inputs are from renewable or non-renewable resources. The emergy evaluation method (Odum, 1996) emphasises how to exploit renewable resources more efficiently, this in turn will help the non-renewable resources last longer. Emergy is an important and novel way of interpreting sustainability in agriculture and it is also being used to measure environmental costs and benefits of the agricultural practices.

Emergy compensates for the inability of money to value non-market inputs in an objective manner. Therefore emergy evaluation provides an ecocentric valuation method (Hau and Bakshi, 2004). Emergy accounting is interested in gathering data related to renewable, non-renewable and imported resources – the resources that contribute to the system being studied. The values for the resources are then converted into a common unit which allows all resources to be compared on a fair basis. Emergy accounting recognises the different qualities of energy or abilities to do work (Hau and Bakshi, 2004).

In ordinary commercial dealings among people, the value of a product or service within the economy is determined by their willingness to pay. People know that money is paid for their work and that money is not paid to the environment. Yet the environment does important work that is essential for all economic activity (Campbell, 2008). Only people can accept money for products and services, so the environment cannot and does not use money as a measure of value. Value in

Table 1: Values for emergy indices found in two farms split into two fields (a and b).

Farm No.	Crop	EYR	ELR	SI
1 (a)	Spring Barley	1.37	2.82	0.48
1 (b)	Winter oilseed rape	1.31	3.37	0.39
2 (a)	Winter Wheat	1.26	4.1	0.31
2 (b)	Spring Oat	1.37	2.75	0.50

an ecosystem is measured by flows of available energy, the available energy with the potential to do work (Campbell, 2008). At present, modern society owes a tremendous debt to the environment, and this debt is not being counted or controlled. The reason being is that we have not had adequate methods for accounting for these debts. However, emergy accounting offers one solution to the problem and allows scientists to be able to record the environmental debts to our society.

Emergy offers an alternative analysis method for extrapolating information related to the sustainability of a system, for example agriculture. The outputs derived from the approach in the form of emergy indices can be used to give recommendations in relation to resource use within a system, and aid best management practices. Future developments may lead to building in the concept of biodiversity, aspects of cropped land (investigating the land margins) and livestock, and climate change. Future modelling development with respect to climate change and biodiversity will aim to look at scales of the whole plant, patch and field with potential outcomes related to modelling carbon and nutrient fluxes, pools and losses.

Research has already raised issues of uncertainty in relation to the use of emergy evaluation for helping to understand our environment, whether it is from an agricultural or economic point of view (Brown and Herendeen, 1996; Hau and Bakshi, 2004; Herendeen, 2004). The main reason for this uncertainty lies in the formulation of the unit emergy values that have been derived for different commodities, as these have predominantly been formed via the application of various assumptions which need to be further qualified (Brown and Herendeen, 1996). Concern is also present in the decisions made for assigning the different resource types – whether a commodity is seen as non-renewable or purchased etc. In many instances, preference still lie in the utilisation of the standard energy analysis methodologies (Herendeen, 2004). Energy analysis is a good starting point for understanding resource use in a particular system, but where emergy accounting differs from energy analysis is that it has the ability to cover all aspects of the system in question and assign values in a common currency for further manipulation and analysis. This is beneficial as it allows for a full cost/benefit analysis to be undertaken for the system in question.

The arable/grass ecosystems of Scotland have many advantages over comparable systems in other parts of the World. They have combinations of temperatures and sunlight that give high potential yields, rich soils which for the most part are not highly erodible given good management, and a high scientific and technical base. They also have the problems that beset intensive agriculture everywhere – the loss of materials causing pollution outside agriculture and the reduction of life forms that are essential for the ecosystem to function as well as providing an aesthetic biodiversity. More specific constraints include limited choices of crops in the rotation, an often difficult and late harvest, high drying costs of produce, and high foliar disease. New management methods, new markets and new crop varieties are needed to solve these problems. But more comprehensively, there is a need to reduce the risk of being constrained by future adverse conditions, whether climatic or economic. The services of our multifunctional agriculture must include the provision of wholesome and affordable food, a supply of food as secure as possible in the face of global events, a living for farmers, a contribution to the economy and a landscape that is aesthetically pleasing and supports visible biodiversity.

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APPENDIX

Table 1: Raw data collected for use in the emergy analysis of Scottish fields. The fields correspond with those highlighted in the main text.

Field	Size	Crop	Seed Rate	Soil Type	N (g)	P (g)	K (g)	S
1(a)	14.28	Spring Barley	195	Sandy loam	40.5	0	0	0
1(b)	20.64	Winter oilseed	5	Medium loam	110.5	48	48	0
2(a)	18.83	Winter wheat	180	Medium loam	183	103	163	0
2(b)	10.18	Spring Oats	250	Loam	0	0	0	0

Table 2: Conversion of the raw data into ENERGY values. Standard values have been used for many variables as full data sets for Scottish agriculture had not been collected. Unity J/yr (unless stated otherwise).

Field	Sunlight	Rain	Earth Cycle	Loss to topsoil	Fuel	Labour	Machinery	N (g/yr)	P (g/yr)	K (g/yr)	Seeds
1(a)	3.7E+13	2.1E+10	3E+10	1.3E+09	0	2.8E+08	6.8E+08	40500	0	0	195000
1(b)	3.7E+13	2.1E+10	3E+10	1.3E+09	0	2.8E+08	6.8E+08	110500	48000	48000	5000
2(a)	3.7E+13	2.1E+10	3E+10	1.3E+09	0	2.8E+08	6.8E+08	183000	103000	163000	180000
2(b)	3.7E+13	2.1E+10	3E+10	1.3E+09	0	2.8E+08	6.8E+08	0	0	0	250000

Table 3: Conversion of the energy values into EMERGY values using the transformity values given in table 5 of the appendix. Units sej/yr unless stated otherwise.

Field	Sunlight	Rain	Earth Cycle	Loss to topsoil	Fuel	Labour	Machinery	N (sej/g)	P (sej/g)	K (sej/g)	Seeds
1(a)	3.7E+13	6.6E+14	1.7E+15	7.9E+13	0	2.1E+15	4.5E+15	1.9E+14	0	0	1.4E+12
1(b)	3.7E+13	6.6E+14	1.7E+15	7.9E+13	0	2.1E+15	4.5E+15	5.1E+14	8.5E+14	1.4E+14	3.3E+10
2(a)	3.7E+13	6.6E+14	1.7E+15	7.9E+13	0	2.1E+15	4.5E+15	8.5E+14	1.8E+15	4.8E+14	1.2E+12
2(b)	3.7E+13	6.6E+14	1.7E+15	7.9E+13	0	2.1E+15	4.5E+15	0	0	0	1.7E+12

Table 4: Emergy values for the resource types and the values for the calculated indices.

Field	R	N	F	Yield	Fraction	EYR	ELR	ESI
1(a)	2.43E+15	7.88E+13	6.78E+15	9.29E+15	0.26	1.37	2.82	0.48
1(b)	2.43E+15	7.88E+13	8.10E+15	1.06E+16	0.23	1.31	3.37	0.39
2(a)	2.43E+15	7.88E+13	9.76E+15	1.23E+16	0.20	1.26	4.05	0.31
2(b)	2.43E+15	7.88E+13	6.59E+15	9.1E+15	0.27	1.38	2.75	0.50

Indices Equations

Yield (Y) = R + N + F

Fraction Renewable = R /(R + N + F)

Emergy Yield Ratio (EYR) = Y / F

Environmental Loading Ratio (ELR) = (F + N) / R

Emergy Sustainability Index (ESI) = EYR / ELR

Where:
R = renewable emergy
N = non-renewable emergy
F = purchased emergy
Y = yielded emergy

Table 5: Values used for the transformity calculations.

Resource	Transformity Value	Source
Sunlight	1.00 E+00 (sej/J)	Ulgiati et al 1994
Rain	3.12 E+04 (sej/J)	Gasparatos et al 2008
Wind	2.47 E+03 (sej/J)	Gasparatos et al 2008
Earth Cycle	5.76 E+04 (sej/J)	Gasparatos et al 2008
Loss from topsoil	6.25 E+04 (sej/J)	Ulgiati et al 1994
Fuel	6.60 E+04 (sej/J)	Ulgiati et al 1994
Labour	7.38 E+06 (sej/J)	Ulgiati et al 1994
Machinery	6.60 E+06 (sej/J)	Ulgiati et al 1994
Nitrogen Fertiliser	4.62 E+09 (sej/g)	Ulgiati et al 1994
Phosphate Fertiliser	1.78 E+10 (sej/g)	Ulgiati et al 1994
Potassium Fertiliser	2.96 E+09 (sej/g)	Ulgiati et al 1994
Seeds	6.60 E+06 (sej/J)	Ulgiati et al 1994

Table 6: Calculations used for conversion purposes within the emergy evaluation

Resource	Calculation
Sunlight	Energy (J/yr) = (land area)(average insolation)(1 – albedo)
Rain	Energy on land (J/yr)= (area)(evapotranspired rainfall)(water density)(free
Earth Cycle	Energy (J/yr) = (land area)(heat flow per area)
Loss from	Energy of net loss (J/yr)= (net loss)(% organic in soil)(5.4 kCal/g)(4186 J/kcal)
Fuel	Energy (J/yr)= (total use)(energy content in kg)
Labour	Total energy input (J/yr)= (total metabolic energy/person/day)(total man days
Machinery	Energy in J/yr
Nitrogen	g/yr
Phosphate	g/yr
Potassium	g/yr
Pesticides	Sum the values (J/yr)
Seeds	Sum total use of seed (kg/yr), transform this into average energy production. Total energy of seeds = total use of seeds x energy for production