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A Life-Cycle Approach to Characterising Environmental and Economic Impacts of Multifunctional Land-Use Systems: An Integrated Assessment in the UK

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Received: 8 November 2010 / Accepted: 30 November 2010 / Published: 15 December 2010

Abstract: An integrated environmental and economic assessment of land use for food, energy and timber in the UK has been performed using environmental Life Cycle Assessment (LCA) and economic Life Cycle Costing (LCC), to explore complementary sustainability aspects of alternative land uses. The environmental assessment includes impacts on climate change, ecosystem services and biodiversity, all of which include soil carbon emissions. The systems explored include all processes from cradle to farm ‘gate’. The crops assessed were wheat and oilseed rape (under both organic and conventional farming systems), Scots Pine, and willow and *Miscanthus*. Food crops, particularly conventional food crops, are shown to have the highest climate-changing emissions per ha, whereas energy and forestry crops show negative net emissions. To a lesser extent, the same situation applies to impacts on ecosystems and biodiversity, with carbon storage in biomass playing a larger role than carbon in soils. The energy and forestry crops in this study show an overall beneficial environmental impact, in particular due to soil carbon sequestration, making these land uses the lowest contributors to climate change. Combining this with the non-renewable CO₂ emissions displaced will mean that energy crops have an even lower impact. Economically, conventional food crops present the highest costs per ha, followed by organic food crops, energy and forestry crops. Integrating the results from LCA and LCC shows that the climate impacts per monetary unit of all land

uses are dominated by soil management and, in the case of food production, also by fertilisation. Taxes or incentives such as “carbon charging” will encourage changes in practice in these areas to improve the sustainability of land management, mainly by building up Soil Organic Carbon (SOC).

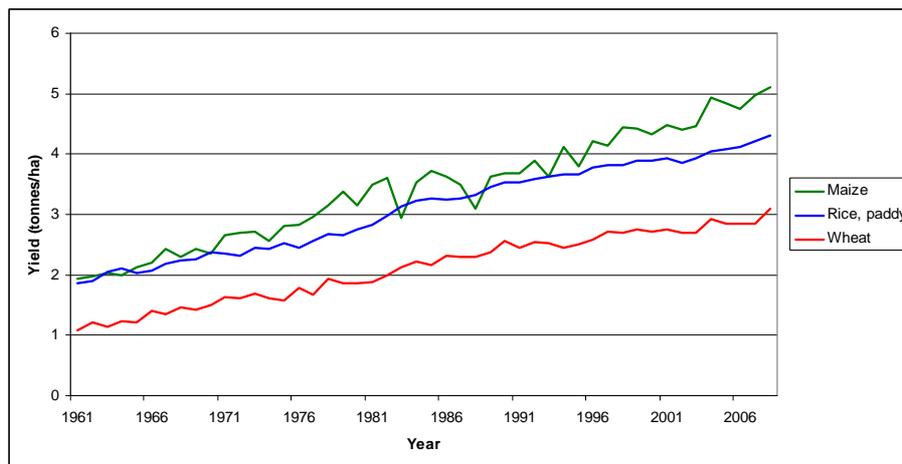
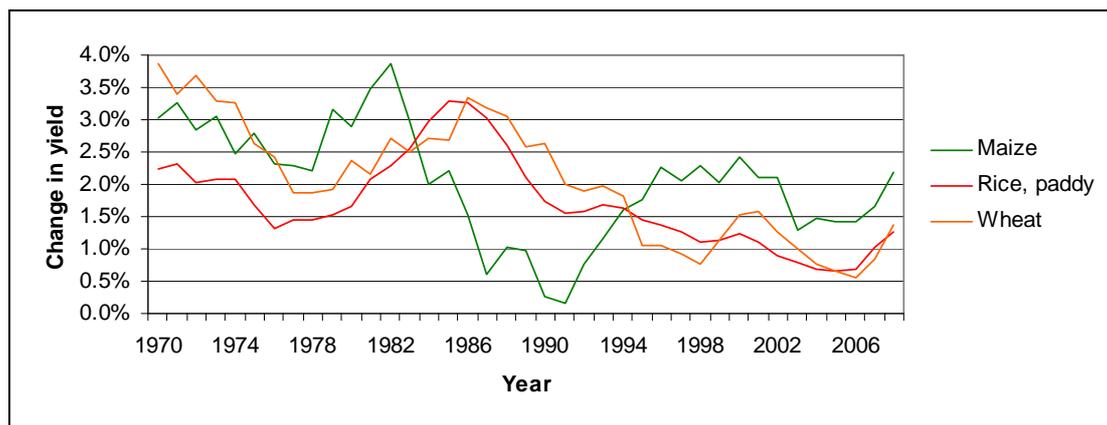
Keywords: life cycle assessment (LCA); life cycle costing (LCC); land use; agriculture; silviculture; energy Crops; bioenergy

1. Introduction

Throughout human history, land use has become progressively more intensive in order to support the demands of an extraordinary human population growth, particularly since the industrial revolution when fossil energy resources replaced their bio-based counterparts. Increases in the productivity of land have even led to a view, almost certainly transient, that land availability is not a constraint on human activities, a view encouraged by general improvements in technology which have resulted in increased production per unit of land. However, high growth rates of the human population emphasise that land is a finite resource with a limited carrying capacity, a potential problem first articulated by Thomas Malthus [1]. Global average yield increases for the three most important staple food crops (wheat, rice and maize) increased between 1961 and 2008, despite some inter-annual fluctuations (see Figure 1), but yield growth rates now seem to be declining, indicating the possibility of a “peak” in the near future at which the maximum rate of global food crop production will be reached and after which it may decline (see Figure 2).

There is a tension between the Malthusian view and the "cornucopian" view [2-4], exemplified by many optimistic biofuel studies [5], that the growth in productivity illustrated by Figure 1 and Figure 2 can provide sufficient food and fuel. This view seems to be unfounded, since positive yield growth rates cannot be sustained indefinitely by technological progress. In addition, all the best land is already under production and, therefore, it is perfectly arguable that marginal yields will be lower than current yields.

Alternative or complementary views about “environmental factors and security” include *Neomalthusianism* (resource scarcity leads to conflict), *Political Ecology* (the issue of security lies in the distribution of resources), *Cornucopianism* (there is no inherent resource scarcity), *Institutionalism* (cooperation overcomes scarcity), *Resource Curse* (resource abundance is the problem).

Figure 1. Global average yield of maize, rice and wheat between 1961 and 2008 [6].**Figure 2.** Cereal yield growth rates (Note: Data represent the average annual percentage increase in yield between successive rolling five-year periods (e.g., data for 1970 refer to the increase in average yield comparing 1966–70 with 1961–65) [6].

In addition to the demand for food to feed an increasing human population, land is increasingly required to provide other materials and energy. A multitude of underlying and interrelated factors—such as demographic growth and affluence, and the overall increase in supply made possible by yield increases—contribute to the general increase in the quantity of land products demanded, exemplified by increasing consumption of meat and dairy produce in China and India. Conversely, in recent years, supply shortages have led to an increase in food commodity prices. Shortages of food supply have partly been created by increased demand for biofuels, as land that is used for energy will not be available for food production. Competition for land between food and energy crops is therefore a serious issue because it might decrease the potential for food production but, most importantly, it will raise the price of food. In fact, the price of food is arguably a more determinant factor of food security than food availability per se. A policy research working paper for the World Bank [7] concluded that the most important factor behind the rapid rise in food prices was the large increase in biofuel production in the US and the EU. The production of first generation biofuels ought to be questioned due to its potential negative effect on food security—a basic human need.

Concerns over global climate change, decreased provision of ecosystem services and biodiversity loss have led to interest in using land in ways that mitigate these threats (e.g., forests, biofuels and bioenergy), particularly in using various forms of bioenergy to displace fossil fuels or to sequester carbon.

Superficial examination suggests that biomaterials and bioenergy should be associated with lower emissions of GHGs than their fossil counterparts, since they form part of the renewable carbon cycle: the CO₂ released on combustion or disposal was originally removed from the atmosphere by the growing plants. However, such a superficial analysis can be misleading, especially for transport biofuels [8]: it is necessary to examine the complete life cycle of the bioproduct. When this is done, not all bioproducts show improved environmental performance [9-11].

Although the primary source of rising atmospheric CO₂ is the use of fossil fuels, historical land use and land-use changes (LULUC) which release carbon from terrestrial ecosystems as CO₂ have contributed more than one-third of the increase in atmospheric concentration of carbon dioxide, the principal Greenhouse Gas (GHG) [12]. Because the global terrestrial stock of carbon in both vegetation and soils represents three times as much as the atmospheric stock [13], those land uses and management practices that influence carbon and other GHG flows are of potentially high importance in climate-change mitigation strategies. Righelato and Spracklen [14] have gone so far as to suggest that “the carbon sequestered by restoring forests is greater than the emissions avoided by the use of the liquid biofuels” due to the C sequestered in the soil and in above-ground biomass, and therefore argue for reforestation and forest maintenance. It is clear that, in contrast to annual crops, perennial cropping systems tend to accumulate Soil Organic Carbon (SOC) and some energy crops, such as Short Rotation Coppice (SRC) willow, can also serve for remediation of contaminated soil [15,16].

Furthermore, indirect effects can be highly significant in the life cycles of biofuels. In addition to the food *vs.* fuel dilemma, unintended consequences arising from indirect land-use changes (iLUC) provide a further argument against the adoption of these fuels. This phenomenon refers to the potential release of additional carbon emissions due to land-use changes around the world induced by the expansion of croplands for biofuel production in response to increased global demand. As farmers worldwide respond to higher crop prices, pristine and set-aside lands are converted to new cropland to replace the feed and food previously grown on land now elsewhere to biofuels production [17-22]. These lands may have a high density of carbon bound in soils and vegetation which, upon conversion, is released to the atmosphere. Consequently, the “carbon debt” [23] of biofuels may be very high and, in some cases, their carbon payback time may be as high as 2,000 years [19,21,24]. The original policy targets [25] of the European Commission on the use of biofuels may have to be revised following the concern expressed by one of its Directorates-General, the Joint Research Centre, that the effects of iLUC may negate any GHG savings from replacing fossil fuels with biofuels [17].

In addition to carbon, the release of nitrous oxide (N₂O), mainly due to fertiliser use, is a major concern [26,27] due to the high potency of this GHG, whose Greenhouse Warming Potential (GWP) is 298 times that of CO₂ on a 100-year timeframe [28].

The high variability in the impacts of bioenergy has led to the development of standards for sustainable bioenergy ([29]). The potential GHG savings from bioenergy and biofuels are not clear and vary widely according to:

- the system delimitation in which the reference systems for land and non-renewable fuels are displaced [18,30,31],
- the crop/feedstock chosen and how it is used (power, heat, CHP, or ethanol and biodiesel for transport), and
- the amount of agrochemicals used [26].

Despite current well-deserved attention to climate change, it is equally important to acknowledge impacts on ecosystems, which are at the base of all bioproducts and many important processes. Indeed, the biological productivity of land-based (*i.e.*, terrestrial) ecosystems is just one of several “services” upon which human existence and welfare depend. The Millennium Ecosystem Assessment [32] identified a range of services provided by ecosystems: “food, water, timber, and fibre; regulating services that affect climate, floods, disease, wastes, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling”. Pressure on ecosystems through changes in land cover and use has led to a decrease in the number and size of habitats for non-human species, but also to a decrease in soil quality. Land use is recognized as the main driver of soil degradation, although soil quality may also be enhanced depending on land management practices. Intensive land use has resulted in biodiversity loss and in an impairment of the ability of ecosystems to function (*i.e.*, to support biodiversity and to provide the above services)—which has led in some cases to desertification [33]. This is a major concern due to the decreasing amount of fertile land per person [34,35]. SOC content is a key component of soil quality, determining several ecosystem services [15,32], and its loss is a major cause of soil degradation [36-39]. However, degradation of soil carbon has not been properly and consistently addressed in the environmental assessment of land-use activities, in particular agriculture and forestry.

In view of the competing demands on multifunctional land—a limited and scarce resource—to feed people adequately, sustain biodiversity and ecosystem services and mitigate climate change, there is a clear need for a systematic basis for allocating land use with respect to economic and environmental objectives. The purpose of this paper is to set out an integrated environmental and economic sustainability assessment, covering the gaps identified above, for comparison of different land-use systems. LCA is used for the environmental assessment, concentrating here on GHG balances as the contribution to global climate change with special emphasis given to establishing a life-cycle approach to assessing land-use impacts on ecosystems. A parallel economic assessment is integrated with LCA, also using a life cycle perspective that covers all activities in the supply chain up to the farm gate. This work contributes to the development of an integrated environmental and economic sustainability assessment method to explore sustainability impacts of alternative forms of using land.

2. Methods

This study forms part of a larger consequential assessment and comparison of the sustainability impacts associated with different land-use systems for food, forestry and energy production in the UK [40]. It uses a combination of LCA and LCC. In this paper, an attributional approach is followed.

LCA is a systems analysis tool that provides information on the full environmental effects of a product, service or system from its cradle (extraction of raw materials) to its grave (waste

management). It gathers information on all the inputs to and outputs from a product system including releases to the environment, and assesses the potential environmental impacts associated with these inputs and outputs [41-46].

The particular method for accounting for the impacts on ecosystem services and biodiversity is described in the section 2.7. *Impact Assessment*.

LCC is a complementary tool which provides an economic analysis of the operations making up the supply chain providing a product or service, concentrating on the economic cost at each stage. There are three types of LCC: conventional, environmental and societal [47], the latter two including a varying degree of the different types of externalities. Conventional cradle-to-gate LCC was applied here and includes the assessment of all costs associated with the life cycle of the crops specific to each land use that are directly covered by the land manager (*i.e.*, farmer or forester). The exposition here follows the steps in LCA identified in the relevant international standard [48], with the corresponding steps in LCC introduced in parallel.

The relationship between environmental impact and economic value or cost, quantified by ratios termed ecometrics [49], can be used to identify products or processes associated with environmental impacts disproportionate to their economic cost and therefore to be targeted for environmental improvement [50]. Applying the principle of Environmental Justice which is a concern for sustainability [51], disproportionate environmental impact in part of a supply chain—usually primary production [52]—indicates lack of equity and therefore unsustainability in the supply chain [53], because an operator is either suffering local environmental damage without economic compensation or causing impacts, such as climate change, affecting others without compensating for the “externalities”. The Fair Trade movement [54] is one of the most conspicuous attempts to improve sustainability by achieving more equitable distribution of benefits and impacts along supply chains. This approach is applied here by integrating the results of LCA and LCC. However, the focus on land use limits the assessment to the first part of the supply chain, *i.e.*, up to the farm gate. The analysis, therefore, will not indicate inequality in terms of the distribution of value along the supply chain, but rather the relationship between the environmental impacts and economic costs of management practices (e.g., soil management, fertilisation, harvesting and storage) for each land use.

2.1. Goal and Scope

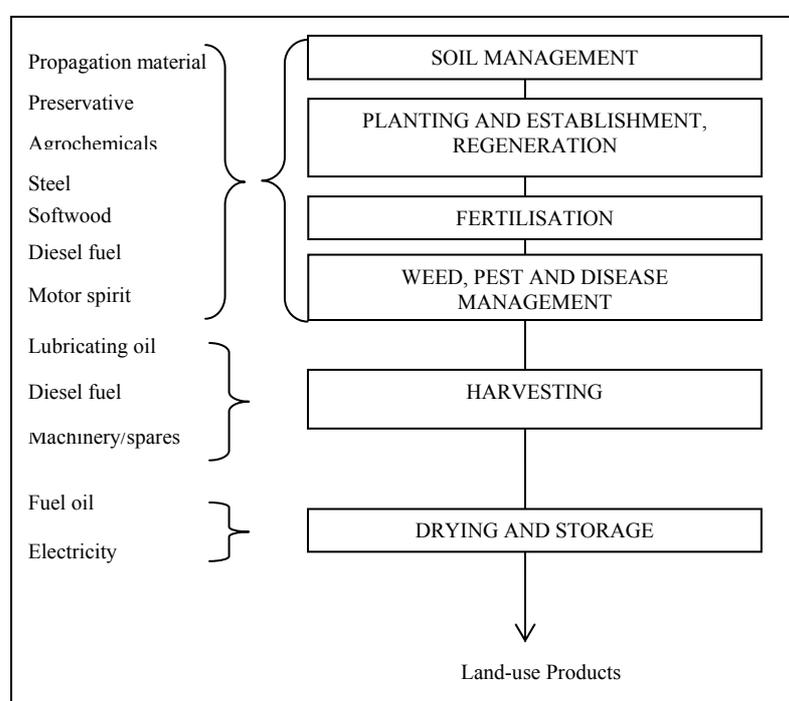
The focus of this study is the environmental and economic impact of the cultivation of food, energy and forestry crops, to inform policies on land use to produce food and energy crops. The scope covers the ‘cradle-to-gate’ part of the supply chain, from extraction of raw materials, through agricultural activities and cultivation, to harvesting and preparing the crop for transport from the “farm gate” in an “attributorial” approach. The overall aim is to compare different options for using and managing agricultural land. The specific objectives are:

- To characterize, compare and contrast, environmentally and economically, the main supply chains of the products arising from land use for biotic production of food, energy and timber in the UK;

- To determine which life cycle stages of the different products contribute most to overall GHG emissions from each system, and to the impacts on the provision of ecosystem services and on biodiversity.
- To compare the environmental and economic performance of different product systems and investigate the relationship between them as a guide to sustainability.

Given the aim and objectives, the basis for comparison (known as the functional unit in LCA) is one hectare of land for one year, rather than the more common basis of a unit of product. The focus is on the foreground agricultural activities, including drying and storage, although production and use of fertilisers and pesticides are included. The activities covered comprise: soil management, fertilisation, weed, pest and disease management, harvesting, storage and drying. The inputs considered include agrochemicals, cuttings/setts, liquid fuels, lubricating oil and machinery/spares plus softwood, cuttings, steel and preservatives used for fencing (see Figure 3). The systems described are averages to represent typical UK practice, e.g., crop yield, rate of agrochemical input use, electricity grid mix, other inputs and outputs, and management practices. The LCC assessment is focused on real, internal costs without end-of life or use costs as these are borne by others (*i.e.*, non-land managers) in the post farm-gate stages of the life cycle of the land-use products. The perspective is, therefore, that of one market actor: the producer. Economic returns to the farmer are excluded from the analysis because they do not relate to particular stages of the cradle-to-gate analysis, although this consideration is of vital importance in decision-making regarding land use.

Figure 3. Flow Chart for the Production of Land-use products from 1 ha of land.



2.2. Systems Description

Three different land uses have been considered: food, energy and timber, chosen as representing either current UK crops or crops which are currently promoted, such as biomass energy crops. These

are represented by five crops: wheat (*Triticum aestivum*), oilseed rape (*Brassica napus*), Miscanthus (*Miscanthus x giganteus*), willow short-rotation coppice (*Salix viminalis*) and Scots Pine (*Pinus sylvestris*). Food crops are further represented by both organic and non-organic (or conventional) management regimes. No allocation of environmental burdens between co-products (grain and straw; sawlogs, roundwood and forest residues) is needed because it is the land use, not the products, that is being assessed.

The total land under agricultural cultivation in the UK is 18.8 Mha [55], representing 77% of total land area, the rest being divided roughly equally between forests and urban areas. Land use for food is represented by two crops under two management systems: conventional and organic wheat and oilseed rape, although it is recognized that these crops may also be used for liquid biofuel production (and, hence, would be considered under an energy land use). According to the Forestry Commission [56], forestry occupies 2.8 Mha in the UK; Scots Pine is considered here as a popular forestry crop. Willow under a short-rotation coppice (SRC) regime and Miscanthus are adopted as these energy crops are suitable for UK conditions. Their current proportion of agricultural land use is insignificant (<0.01%) but will grow substantially if the market for energy crops develops [18].

2.3. Land Use for Food: Wheat and Oilseed Rape

Food cropland accounts for one-third of the total agricultural area [55]. The most widely-produced crop in the UK is wheat (*Triticum aestivum*), accounting for some 1.8 Mha (~10% of agricultural land) representing 40% of arable land and 58% of cereal land [55] of which 99% is dedicated to conventional production [57]. In terms of land use, oilseed rape follows wheat and barley (which is mainly used for feed), occupying 0.6 Mha. Therefore, the representative food crops considered are wheat and oilseed rape, under both conventional and organic [58] types of management in order to reflect different levels of intensity of production. Extensive wheat production is based on organic wheat.

Organic crop production is an alternative to conventional fossil-resource reliant intensive production, focused mainly on the production stage of the chain. Organic, or ecological, farming differs from conventional farming in the production stage of the supply chain by having higher environmental and animal welfare standards, and specifically by using rotations, leys and green manures to achieve nutrient self sufficiency at farm-level. In spite of its higher use of farm machinery for weed control (which releases carbon dioxide to the atmosphere), organic farming relies on organic matter inputs (such as straw, manure and compost) to maintain soil fertility, and thereby both increases soil organic carbon levels and avoids the GHG emission associated with production and use of agrochemicals, mainly nitrogen fertiliser.

The life-cycle environmental impacts may be less intensive than their conventional counterparts per unit of land area. However, per unit of output e.g., metric tonne, the difference may be reversed as those same input restrictions for organically-managed land often result in lower yields [59], thus requiring more land to produce the same amount of products (which are typically more expensive than their conventional counterparts).

Despite aiming at increasing the sustainability of food systems, the lower intensity of an organic system results in lower yields and therefore lower land-efficiency. The relatively low environmental impacts (from not using synthetic fertilisers) may, thus, be offset by lower yields [57].

Oilseed Rape (OSR) is chosen because of its popularity in UK as a non-cereal arable crop, using some 13% of arable land (and 95% of oilseeds land) in the UK [55]. OSR is an annual crop, farmed primarily for its vegetable oils, used in human food. However, OSR is becoming increasingly popular for production of biodiesel due to its high oil content. The proportion of land devoted to organic production is slight, at 0.02%.

The assumed yields and inputs of wheat and OSR are shown in Table 1. Here, organic production of wheat and OSR is some 42% and 47% lower, respectively, due to much lower fertiliser inputs.

Table 1. Selected input data for UK oilseed rape for food (extrapolated from [57]).

	Conventional		Organic	
	Wheat	Oilseed Rape	Wheat	Oilseed Rape
Grain yield (t ha ⁻¹ yr ⁻¹)	7.68	3.20	4.12	1.71
N fertilisation (kg N ha ⁻¹ yr ⁻¹)	219	204	10.5	10.5
Main source of N	Ammonium Nitrate		Compost	
P fertilisation (kg P ha ⁻¹ yr ⁻¹)	20.7	16.9	13.4	9.6
Main source of P	Triple Superphosphate		Rock Phosphate	
K fertilisation (kg K ha ⁻¹ yr ⁻¹)	39.1	25.6	45.2	12.6
Ca fertilisation (kg Ca ha ⁻¹ yr ⁻¹)	96.6	241.2	70.4	171.6
Diesel fuel in field operations (litres ha ⁻¹ yr ⁻¹)	228.2	216.9	136.0	187.1
Fuel for drying and storage (MJ ha ⁻¹ yr ⁻¹)*	973	473	522	254

* MJ refers to the total primary energy used.

2.4. Land Use for Energy: Miscanthus and Willow SRC

The ligno-cellulosic crops considered Miscanthus and willow under a short-rotation coppice (SRC) regime, as these are the most relevant for UK conditions. Miscanthus and Willow SRC are the most popular biomass crops in the UK due to their high biomass yield and their attractive GHG balance [18]. Energy crops occupied 13.22 thousand hectares of agricultural land in 2007, of which 9.8 thousand ha (or 67% of the total area dedicated to biomass crops) were occupied by Miscanthus [60]. Their current proportion of agricultural land use is relatively insignificant (<0.1%) but would grow substantially if recommendations by the Royal Commission on Environmental Pollution [61,62] are followed and the market for energy crops develops [18].

Growing these biomass crops results in no crop co-products since all the biomass harvested is used for electricity and/or heat production. Table 2 shows the input data for the production of Miscanthus bales and wood chip from willow SRC.

Miscanthus, also known as elephant grass, is a C4 perennial energy and fibre crop. Alternative uses include animal bedding, paper making, biopolymer manufacture, and biodegradable products production (e.g., flowerpots). Miscanthus is indigenous to Africa and Asia but is now grown commercially in the UK [61,63-66]. Miscanthus is propagated vegetatively from rhizomes or by micro-propagation, from commercially-available materials which can be planted with existing

machinery used for more conventional crops. It takes one year for establishment; weed control and fertiliser inputs are essential at establishment but not subsequently. It is harvested annually in winter by cutting and baling into Heston bales containing 500–600 kg, and stored outside until dispatch to the end user. Miscanthus is a low-input energy crop but yields a commercial output more rapidly and is therefore associated with lower barriers to introduction. It typically has a useful cropping cycle of 15–20 years, yielding up to 20 oven-dry tones [67] per hectare and year ($\text{odt ha}^{-1} \text{ yr}^{-1}$) after a maturing period of two to three years [68,69]. However, improved cultivation practices and cultivars can give higher yield or enable lower quality land to be used [70,71].

Table 2. Selected input data for UK biomass for fuel from Miscanthus and Willow SRC [72,73].

Input	Miscanthus	Willow SRC
Net yield at traded moisture content ($\text{t ha}^{-1} \text{ yr}^{-1}$)	18	14
Traded moisture content (%)	30	50
Yield of biomass ($\text{odt ha}^{-1} \text{ yr}^{-1}$)	12.6	7
N fertiliser ($\text{kg N ha}^{-1} \text{ yr}^{-1}$)	5.26	0
Type of N fertiliser	Ammonium Nitrate	N/A
P fertiliser ($\text{kg P ha}^{-1} \text{ yr}^{-1}$)	4.82	0
Type of P fertiliser	Phosphate	N/A
K fertiliser ($\text{kg K ha}^{-1} \text{ yr}^{-1}$)	5.07	0
Lime ($\text{kg C ha}^{-1} \text{ yr}^{-1}$)	157.89	0
Diesel fuel consumption in cultivation ($\text{MJ ha}^{-1} \text{ yr}^{-1}$)	477	440
Diesel fuel consumption in harvesting ($\text{MJ ha}^{-1} \text{ yr}^{-1}$)	1,158	308
Diesel fuel consumption in handling ($\text{MJ ha}^{-1} \text{ yr}^{-1}$)	847	39

The analysis here is based on the assumption of an effective annual yield of $12.6 \text{ odt ha}^{-1} \text{ yr}^{-1}$ over 15 years following establishment ($18.0 \text{ t ha}^{-1} \text{ yr}^{-1}$ at 30% moisture content) allowing for 10% losses during harvest and baling [74], 3% losses in transport, 15% in drying and storage and 3% during the last transport stage to the plant [68,69,72,73,75]. Data on yield, inputs, outputs, and carbon sequestration have been obtained from the literature [72,73,76–81].

Short-rotation coppice (SRC)—as opposed to the traditional ‘long-rotation’ forestry management—refers to the practice of managing plantations of fast-growing perennial woody crops, such as Willow, in order to maximise its biomass productivity and harvest potential for energy purposes. Coppicing involves the regular harvest of wood from the same tree or shrub. When harvested, chipped and dried, it can be used as a fuel for heat and power generation. There are, currently, around 3,420 ha of SRC in the UK [60,82].

Like Miscanthus, willow is propagated vegetatively using commercially-available cuttings. Pest and weed control are essential in the first two years. After two years to establish growth, the crop is harvested every three years. The productive period of willow is 15 to 30 years [66,72]. The annualised average yield of current cultivars is typically around $10 \text{ odt ha}^{-1} \text{ yr}^{-1}$ [72], but yields are rising with the introduction of improved strains and can be in excess of $20 \text{ odt ha}^{-1} \text{ yr}^{-1}$ (Forest Research, [83]). A 23-year rotation averaging $7 \text{ odt ha}^{-1} \text{ yr}^{-1}$ is assumed here, although rotations can last for 30 years. Biomass yields for the whole rotation are therefore assumed to be 161 odt ha^{-1} .

There are different harvesting techniques: combined harvesting and baling, and stick harvesting and baling. The latter was assumed here as it is common practice in the UK [72]. The harvested crop is commonly stored on-farm as billets. It can then be chipped or processed into granules [84].

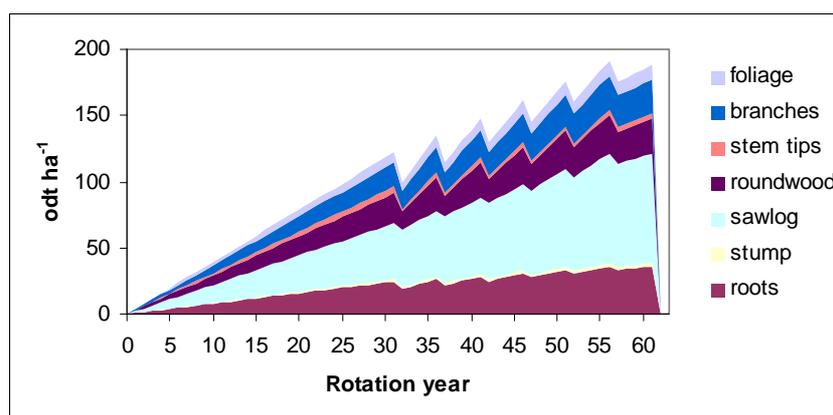
Wood chips are combusted for the production of power, heat or CHP.

2.5. Land Use for Timber: Scots Pine

Commercial forestry and forests are a major land-use in the UK, occupying 2,841 ha (12.5% of total) [56]. Scots Pine is considered here as a popular forestry crop in the UK.

Typical forestry practice in the UK is represented in this work by production of Scots Pine, based on Elsayed [72]. A 63-year rotation is assumed here. According to the BSORT model [85], the total harvest is based on yield class 8 (*i.e.*, $8\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$ stem volume production over the rotation), resulting in a total yield of 97 odt ha^{-1} of sawlogs, 75 odt ha^{-1} of roundwood, 63 odt ha^{-1} of roots, 45 odt ha^{-1} of branches, 20 odt ha^{-1} of foliage, 12 odt ha^{-1} of stem tips, and 5 odt ha^{-1} of stump, over the course of the rotation [85], as shown in Figure 4.

Figure 4. Total biomass production from a 63-year Scots pine rotation [85].



2.6. Inventory Analysis

Inventory Analysis refers to the process of compiling quantitative data on the inputs to and emissions from the supply chain under study. The activities covered comprise: soil management, fertilisation, weed, pest and disease management, harvesting, storage and drying. The inputs considered include agrochemicals, cuttings/setts, liquid fuels, lubricating oil and machinery/spares plus softwood, cuttings, steel and preservatives used for fencing (see Figure 3).

UK-specific technical, economic and environmental data based on common practice in the field in the UK have been used, which were collated from various studies [64,66,72,86]. Generic LCA data used for various operations include fuel and electricity (UK generating mix). Nutrient-related emissions from soil (N_2O ; CH_4) have been obtained from literature values [72]. Effects of land management on SOC were estimated from Smith *et al.* [87], Smith *et al.* [88] Grogan and Matthews [89,90], Arrouays *et al.* [91], Guo and Gifford [92], Bradley *et al.* [93], Dawson and Smith [76] and the final values adopted are shown in Table 3. All C captured as SOC is assumed to come from atmospheric CO_2 through photosynthesis, with all SOC degraded emitted to atmosphere as CO_2 .

For LCC, the equivalent data refer to economic values. In this work, they were obtained from the Farm Management Pocketbook [66].

2.7. Impact Assessment

Conventionally, the next phase in LCA, termed Life Cycle Impact Assessment (LCIA), is to classify the inputs and emissions to express their significance in terms of contributions to a recognized set of environmental impact categories. As explained in the Introduction, two impact categories were selected for specific attention: climate change and provision of ecosystem services and biodiversity. Contributions to climate change were estimated using IPCC's Global Warming Potential (GWP) method [28] but extended to include carbon released by loss of SOC. The impact on ecosystem services and biodiversity has been accounted for using the concept of Ecosystem Carbon Stock (ECS). These developments are explained below.

Table 3. Carbon stocks and flows in different land uses in UK (cold temperate, wet) in soil and biomass (extrapolated from [76,77,94,95]).

Land-use type	Average carbon stocks (t C ha ⁻¹)		Average carbon flows (t C ha ⁻¹ yr ⁻¹)	
	Soil	Biomass	Soil	Biomass
Native Ecosystem (Temperate Forest)	95.0	123.4	0.300	5.6
Conventional Wheat	65.6	3.0	-0.400	6.0
Organic Wheat	77.4	2.0	0.250	4.0
Conventional OSR	65.6	1.7	-0.400	3.3
Organic OSR	77.4	1.3	0.250	2.5
Miscanthus	83.2	16.6	0.620	7.5
Willow SRC	79.5	15.2	0.136	4.2
Scots Pine	95.0	95.5	0.320	5.0

^a Negative value indicates C-emission to atmosphere.

For the climate change impact—measured with GWP—it is assumed that all SOC released is converted to CO₂. 1 kg C stored in soil (a positive value in Table 3) is equivalent to the GWP of -3.67 kg CO₂-eq. (based on the conversion of 44 kg CO₂/12 kg C), whereas 1 kg C released to the atmosphere from SOC degradation has a GWP of 3.67 kg CO₂-eq. The results will refer to total net GHG emissions over one year from the different cultivation systems. However, important considerations for carbon footprinting that are not accounted for here include the progressive and cumulative build-up of carbon, primarily in the soil, and the length of its storage [96-101]. In addition to long-term carbon sequestration, even delayed release of carbon as GHGs reduces the contribution to Greenhouse Warming Potential over the conventional 100-year accounting period [101-105]. Allowing for this delayed release would further improve the net GHG of those activities which increase carbon in biomass and soils; *i.e.*, energy crops and forestry.

The indicator for impact on ecosystem services and biodiversity is based on an extension of the concept of impact on soil quality through changes in SOC as defined by Milà i Canals *et al.* [35]. The impacts of production systems on the ability of ecosystems to provide services and support biodiversity have not traditionally been included in LCA, or indeed in environmental assessments in

general. Many ecosystem services are dependent on the ability of the soil to function ecologically (*i.e.*, soil quality), which in turn is correlated with the amount of organic matter present [106]. Soil organic matter is measured as density of SOC. Biomass is also important as it harbours and feeds biodiversity, in addition to protecting the soil. In particular, above-ground biodiversity depends on biomass for both food and shelter, while below-ground biodiversity is intrinsically linked with SOC content [107,108]. The relationship and overlap between carbon stocks and biodiversity is explored by Strassburg [109], who found a strong association between carbon stocks and species richness. They calculated the Spearman's rank (r_s) correlation coefficients for the relationship between carbon and several biodiversity indices. The resulting $r_s = 0.82$ suggests a strong correlation.

The magnitude of the change in carbon stock levels in both biomass and soil organic matter is therefore proposed as a proxy indicator for impacts on ecosystem services and biodiversity within LCA of land-use systems: an increase in the carbon stock due to the land management practices implies a benefit, whereas any decrease is accounted as a damage to the system. The total of SOC and carbon in biomass is termed Ecosystem Carbon Stock (ECS). The impact on ecosystem services and biodiversity is measured as a carbon deficit (or credit, expressed by negative values) with the unit 't C year', referring to the extra amount of carbon temporarily present or absent from land due to the system studied, when compared to a reference system. The reference system is the potential land cover which, in this case, is assumed to be the natural cover for the UK (*i.e.*, temperate forest). This indicator includes the carbon foregone as a result of removal of land cover through land-use change, regardless of the length of time into the past it actually happened.

The general formula used to calculate characterization factors (CF) for the different crops is shown in Equation 1; see Figure 5 for an illustration of the formula's parameters.

$$C \text{ deficit } [tC \text{ yr ha}^{-1} \text{ yr}^{-1}] = \frac{(ECS_{pot} - ECS_{ini}) \times (t_{relax} - t_{ini}) + \frac{1}{2}(t_{relax} - t_{ini}) \times (ECS_{ini} - ECS_{fin})}{(t_{fin} - t_{ini})} \quad (1)$$

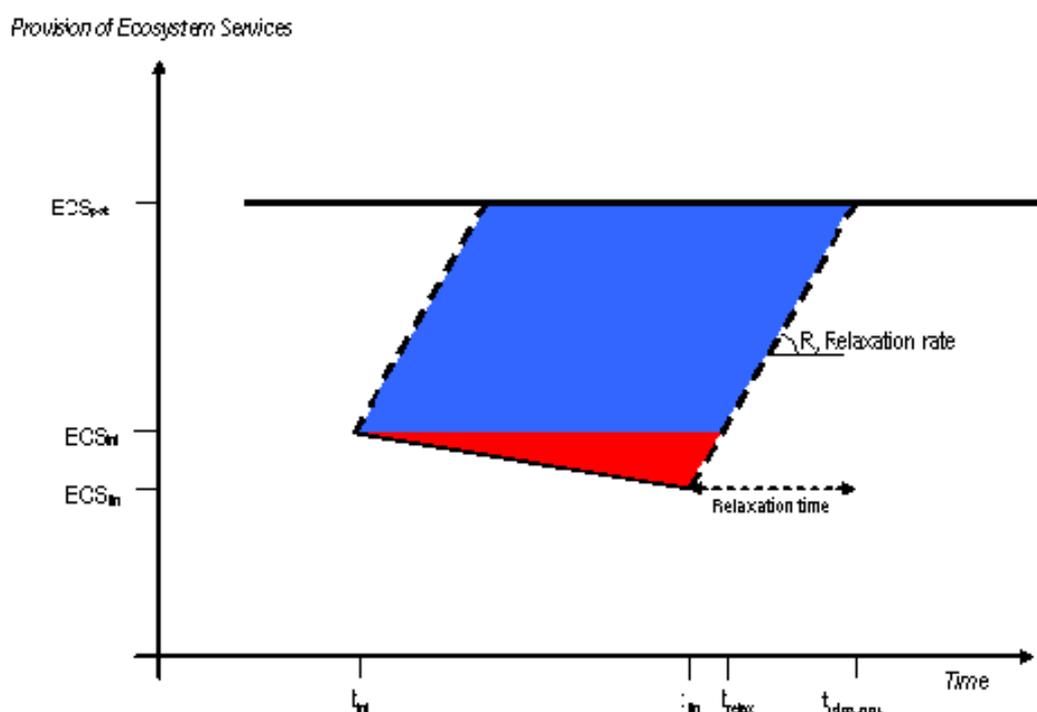
Here ECS_{pot} is the potential level of ECS if land is left undisturbed (as temperate forest); ECS_{ini} is the ECS level at the start of the land use studied; ECS_{fin} is the ECS level at the end of the cultivation period; t_{ini} is the moment when the studied land use starts; at t_{fin} the land use finishes; at t_{relax} , the carbon stock has reverted to the level prior to land use; and $t_{relax,pot}$ is the time when the system reaches its potential level. t_{relax} may be calculated from the relaxation rate R (see below). The equation assumes very simplified evolution of provision of ecosystem services and biodiversity. The first component of the numerator refers to the impacts due to the postponed relaxation of the system (blue area in Figure 5), whereas the second component is the "triangle" in red, referring to the impacts due to the change in provision of ecosystem services and biodiversity during the occupation. The denominator serves to express the characterization factors per ha-yr (all the ECS values are expressed per ha).

The following assumptions have been made:

- As justified above, the magnitude of the difference between the actual and the potential amounts of carbon in both biomass and soil is proportional to the impairment of the ability of ecosystems to provide services and to the impact on biodiversity, since these are directly and indirectly affected by the presence of carbon in biomass and soils.

- There is no change in the ability of land to provide ecosystem services and to support biodiversity in the reference system.
- The potential levels of carbon in soil and vegetation for UK is 96 and 57 t C ha⁻¹ (temperate forest) [110]
- Changes in ECS due to land use have been assessed relative to a situation where this activity is not undertaken. The relaxation rate (R) has been estimated as 0.45 t C ha⁻¹ yr⁻¹ for soil carbon ([91], pp. 160, 171] and 3.20 t C ha⁻¹ yr⁻¹ for biomass carbon [110].

Figure 5. Calculation of impacts on ecosystem services and biodiversity measured by ECS, adapted from [111].



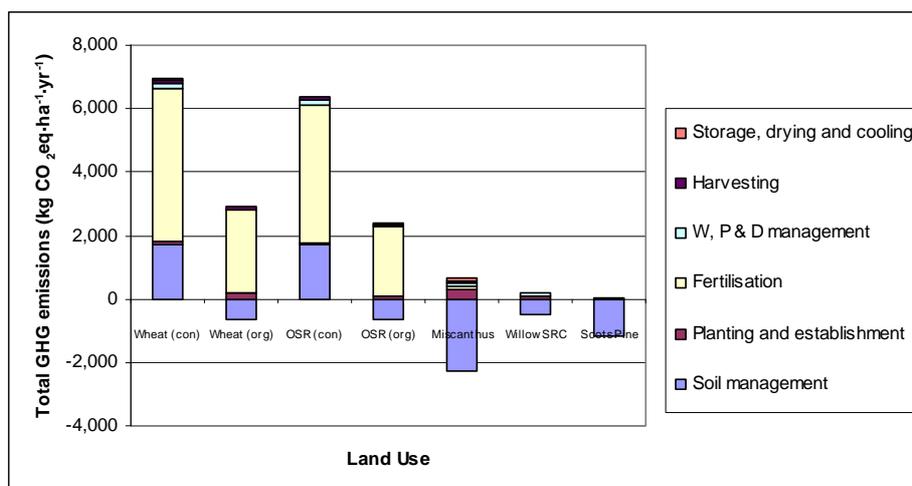
3. Results and Discussion

3.1. Environmental Profile

Global Warming

Figure 6 shows total GHG emissions over one year from the different cultivation systems, including releases due to loss of soil carbon, distinguishing between the different life cycle stages. Emissions are clearly dominated by changes in SOC due to soil cultivation and by fertiliser use, primarily due to field emissions of greenhouse gases, mainly N₂O from soil, with additional emissions of CO₂ and N₂O from fertiliser production. For Miscanthus, willow SRC and forestry, SOC sequestration more than compensates for the emissions (see Table 3).

Figure 6. Total GHG emissions arising from different land management strategies, including release of CO₂ from land (soil management phase).



3.2. Ecosystem Services and Biodiversity

The effect of the different land-uses on ecosystem services and biodiversity is shown in Figure 7, which is based on the differences between average carbon stocks of the different land uses and that of the reference undisturbed ecosystem (see Table 3).

Figure 7. Land use impacts on ecosystem services and biodiversity at the cropping stage—C deficit (t C yr ha⁻¹ yr⁻¹).

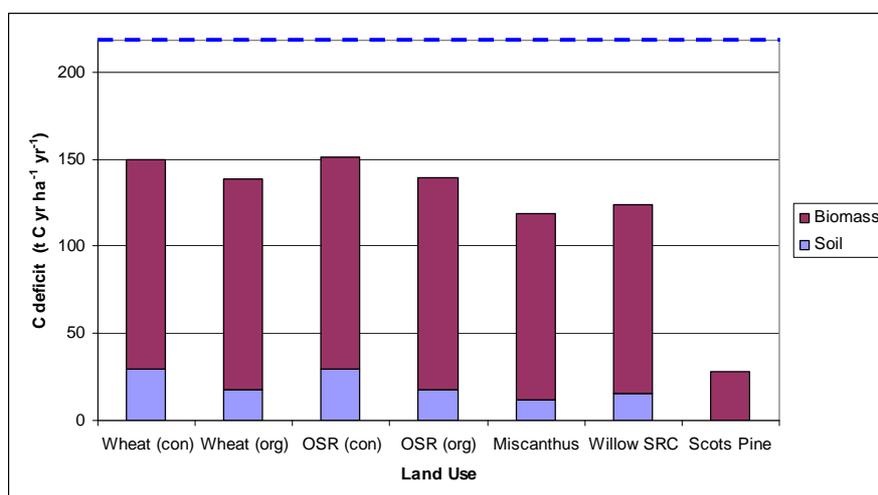


Figure 7 shows that the food crops have a relatively high impact, in particular due to the appropriation of biomass that would have covered the land had it been left to “relax”, *i.e.*, the land cover is restored by spontaneous plant succession in the absence of human intervention. This reference land cover is appropriate for an attributional approach comparing different options in relation to land not devoted to human use. Alternatively, in a consequential approach to assess the results of increased crop production, an appropriate reference land use would be that displaced by production of the crop under study.

Organic arable crops show a slightly lower net impact because they maintain higher levels of SOC, counter-balancing their slightly lower biomass production. Energy and, particularly, forestry crops show the lowest impact on ecosystem services and biodiversity due to the relatively high amount of carbon they accumulate in both biomass and soil.

3.3. Integration of Economic and Environmental Profiles

Table 4 and Figure 8 show the economic costs of the land management activities. For food crops, costs are dominated by post-harvest processing—storage, drying and cooling—and, particularly in conventional cereal production, weed, pest and disease management. Other land uses present lower costs.

Table 4. Economic costs of land uses (collated from [59,66,112]).

	Wheat (con)	Wheat (org)	OSR (con)	OSR (org)	Miscanthus	Willow SRC	Scots Pine
Soil management	86.5	97.9	83.3	92.2	23.5	2.4	8.6
Planting and establishment	43.0	85.0	30.0	60.0	100.0	51.7	14.4
Fertilization	113.5	62.5	124.6	71.9	8.1	0.0	2.7
Weed, pest and disease management	186.2	0.0	175.7	0.0	1.6	68.8	35.4
Harvesting	82.5	82.5	74.4	82.0	19.5	100.0	5.2
Storage, drying and cooling	333.9	179.2	143.3	76.9	2.4	0.0	0.0
Total	845.7	507.1	631.3	382.9	155.0	222.9	66.3

Figure 8. Total costs arising from different land management strategies.

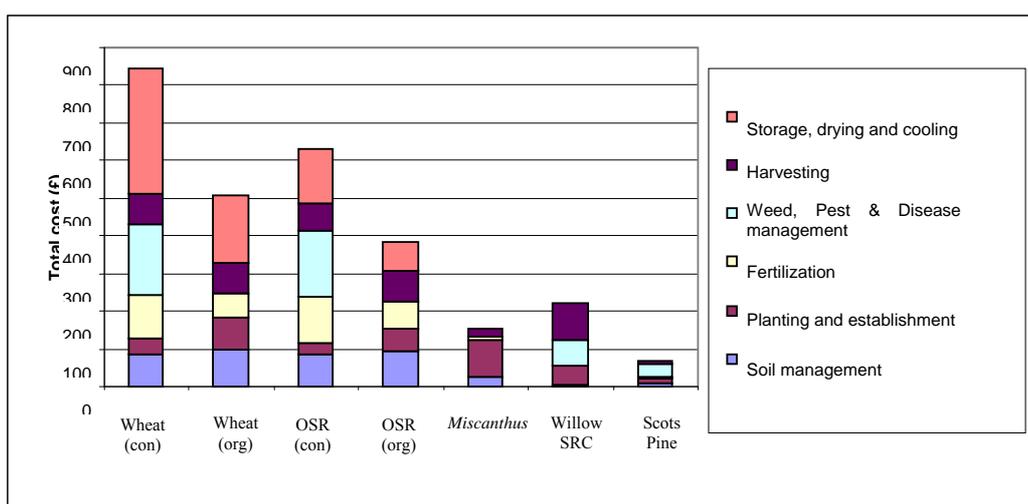


Figure 9 to Figure 13 show the relationship between GWP and economic cost of the land-use management activities. This form of plot provides a visualization of the relationship between LCC and LCA results: a high gradient on any activity of the curve shows that the environmental impact for that part of the supply chain is disproportionately large compared to its economic significance [50].

Figure 9 and Figure 11, referring to the two conventional food crops, show the kind of shape commonly encountered: the early stages in the supply chain—soil management and fertilization in

these cases—are associated with disproportionately high GHG emissions, whereas the emissions from the other stages in the supply chain show comparable emissions per economic cost. Therefore soil preparation and fertilization are the operations to be targeted for environmental improvement, for example non-tillage preparation to reduce emissions from soil carbon and use of fertilisers whose production is associated with much lower GHG emissions (e.g., by applying carbon capture and storage to fertiliser production). Put differently, introduction of significant emission taxes will impact disproportionately on these operations. By contrast, the overall GHG emissions for organic food production (Figure 10 and Figure 12) are much lower, mainly because soil management in these systems sequesters carbon rather than releasing it, at the expense of slightly higher costs. Thus high taxes for GHGs could change the economics to favour organic production, even though fertilization is also a dominant source of GHG emissions even for organic production, although to a lesser extent.

With the current cost structures, different stages dominate the economics for the different crops. Weed, pest and disease management, stage 4, represents one of the main costs for conventional wheat and oilseed rape, as well as for Willow SRC and Scots Pine, all with relatively low impact in terms of GWP. Storage, drying and cooling also presents one of the larger costs for the food crops, again with a relatively small impact in terms of GWP.

- 1 - Soil management
- 2 - Planting and establishment
- 3 - Fertilisation
- 4 - Weed, pest and disease management
- 5 - Harvesting
- 6 - Storage, drying and cooling

Figure 9. Conventional Wheat.

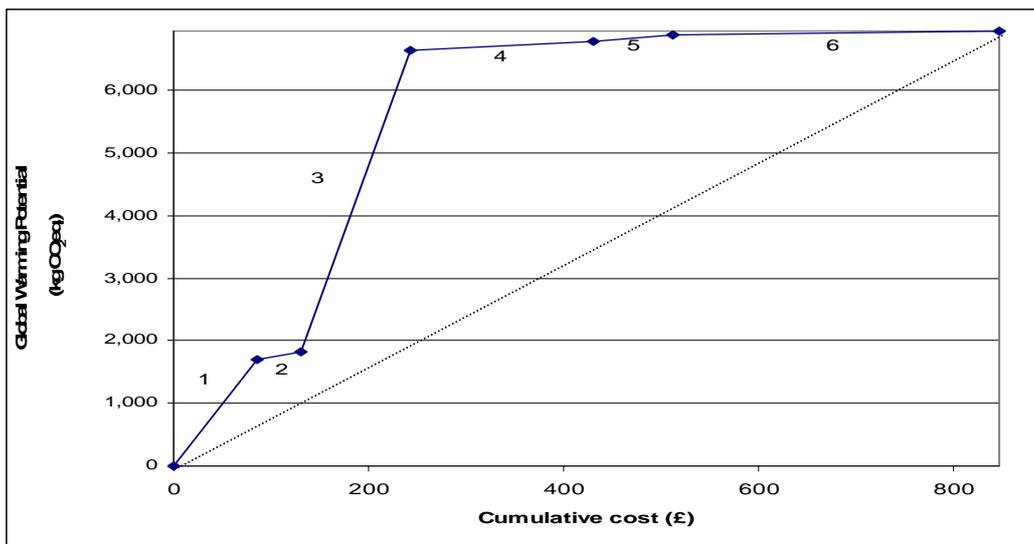


Figure 10. Organic Wheat.

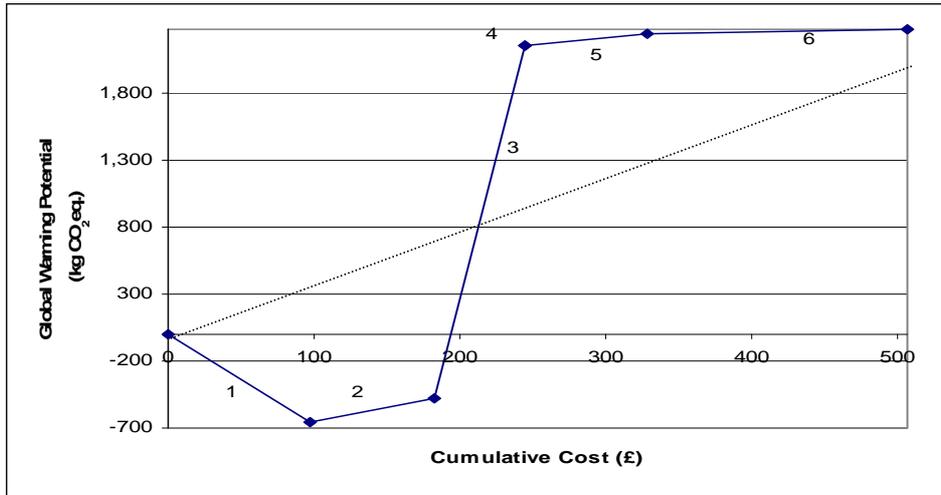


Figure 11. Conventional Oilseed Rape.

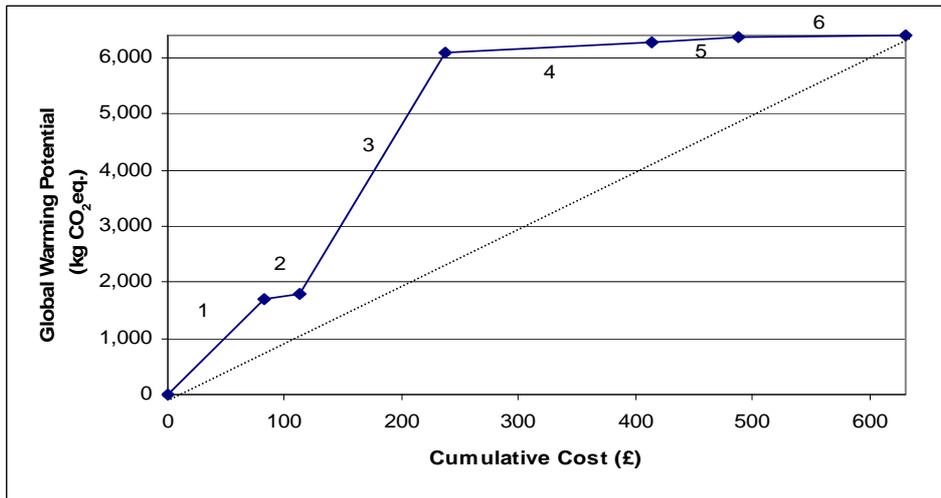


Figure 12. Organic Oilseed Rape.

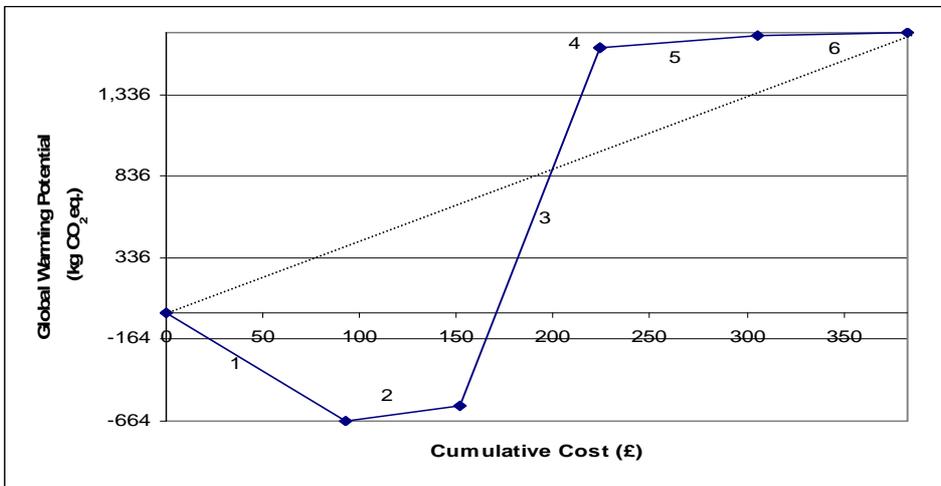


Figure 13. Miscanthus.

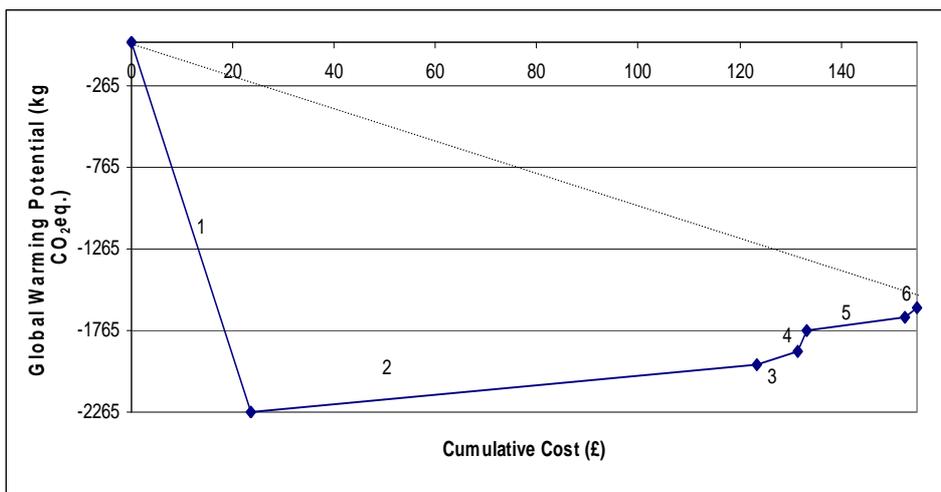


Figure 14. Willow Short-Rotation Coppice.

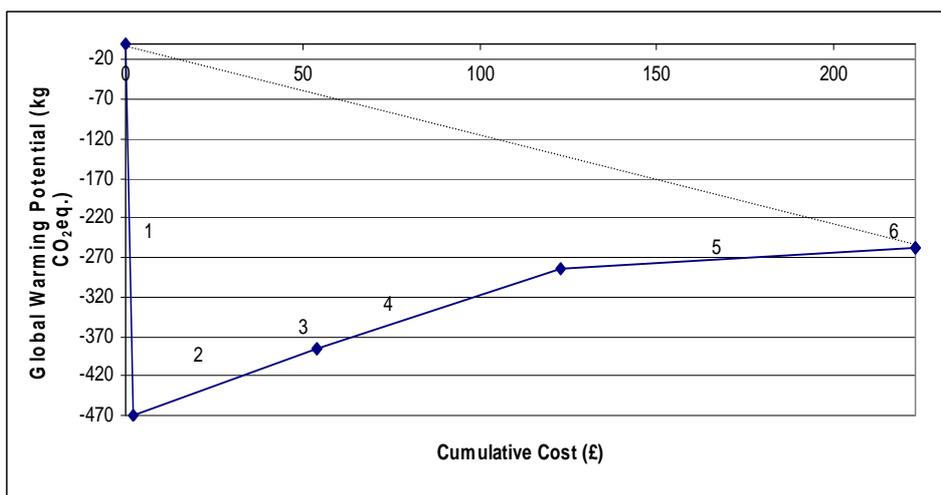
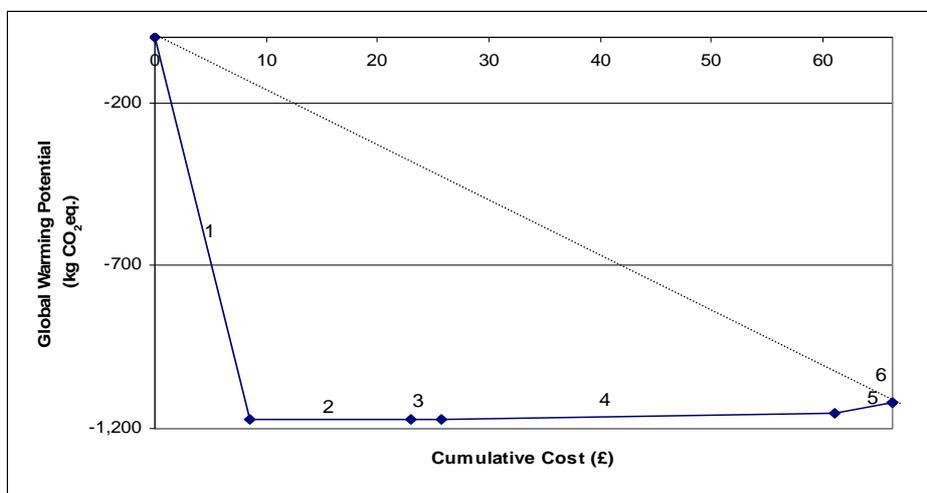


Figure 15. Scots Pine Forest.



Overall, other than fertilization of conventional food crops, soil management has the greatest influence over positive or negative GHG emissions although the economic significance of this part of overall cultivation is relatively small. Harvesting (stage 5) and storage, drying and cooling (stage 6) are associated with the smallest contribution to climate change per unit of economic value. This parallels a trend already noted for manufactured goods, where the later processes in the supply chain—assembly and finishing—tend to be associated with high added value but relatively low environmental impact. However, the steps in the supply chain are all interdependent; thus the curves in Figure 9 to Figure 15 show the relationship between them but individual steps cannot be addressed in complete isolation. Indeed, the importance of each step in the attainment of high-output marketable crops cannot be underestimated, and neither can the gross margins that the farmers or other land-managers get, which is a decisive factor in the allocation of land to alternative crops (see Table 5). Gross margins refer to the difference between revenues from crop sales and the variable costs related to the activities identified above (e.g., seeds and agrochemicals).

Table 5. Economic gross margins (£) of land uses (collated from [59,66,112]).

Wheat (con)	Wheat (org)	OSR (con)	Miscanthus	Willow SRC	Scots Pine
359	505	248	75	115	166

4. Conclusions

This study has shown that, for assessing the environmental sustainability of agricultural activities, it is useful to extend the impacts considered in Life Cycle Impact Assessment to include changes to both above- and below-ground carbon as an indicator of impacts on ecosystem services and biodiversity. Combining LCA with LCC reveals the relative environmental and economic significance of different stages in the cultivation of food and energy crops. Although both environmental and economic factors depend on local conditions and management practices, the differences found between different land uses are so large (in the general rather than the statistical sense) that they are revealed by considering representative cases and may be considered significant.

Despite the small differences, of the seven land uses studied food crops show the biggest impacts on ecosystem services and biodiversity (measured in terms of foregone ecosystem carbon) because use of land for arable crops causes the greatest reduction in ECS relative to land in an uncultivated state (see Figure 5). It should also be noted that land use impacts are multi-faceted, including effects on e.g., water quantity and quality [35,70,113-115]: ECS does not indicate all possible impacts on ecosystem services and biodiversity, so that complementary indicators may be required in specific cases.

Changes in SOC and field emissions due to soil management and fertilization dominate the GHG emissions. It is thus important to consider changes in SOC in LCA studies of land-use products, and challenge the results of those studies not including them. However, it must be noted that estimates of changes in SOC are highly dependent on the input data for the initial SOC level and on the reference system used for comparison [116]. Furthermore, SOC evolution depends strongly on management practices and location so values to be used in analysis must be determined with care and properly justified. In this work, the estimates are all derived from literature values.

The differences in the magnitudes of the carbon stocks associated with the different land uses is substantial and worth exploring as an aid to the development of an overall strategy for reducing the concentration of greenhouse gases in the atmosphere. It is probable that the economic performance of the land uses would be affected if farming were subject economic incentives related to carbon emissions and storage (e.g., a carbon levy, sequestration subsidy, emission permits). In particular, the perennial and non-food land uses would benefit from carbon pricing. Even organic farming would be relatively compensated as a food land use with lower carbon emissions than its conventional counterpart per unit of land area, but the comparison may be reversed when based on equal quantities of product. Energy crops, particularly perennials, are generally associated with lower impacts per unit land area than food, but this simple comparison does not allow for the displacement of food production to other areas.

Before dedicating land to energy, it is worth exploring the current energy resources that are under-utilized, in particular those related to waste. The optimization of land use and of the use of agricultural waste, in particular, needs to be explored more deeply as their interaction is complex and the potential to displace other products is crucial but generally not clear. Similarly, alternative land uses for energy, such as solar and wind, may well provide a more efficient use of land than the options reported in this paper [117], despite their currently prohibitive cost.

The sustainability assessment of land-use activities benefits from an integrated approach, combining environmental and economic (and, eventually, social [118]) analyses, an example of which has been given here showing which stages have an environmental significance disproportionate to their economic significance. The land uses analysed here show that cultivation, rather than harvesting and subsequent processing, is associated with disproportionately high GHG emissions, due to field emissions from fertiliser use and from oxidation of soil carbon. This suggests that modifications to farm practices, such as cultivation without tilling, may be the most cost-effective ways to reduce environmental impacts.

Integrating the results of LCA and LCC reveals the trade-offs between cost and environmental impact which may complicate decision-making for policy. However, it also identifies which activities of the cradle-to-gate part of the supply chain should be targeted for environmental improvement, even at the expense of increased cost.

Analysis of competition for land between food, energy crops and other uses requires further assessment, using a “consequential” LCA and LCC approach [42] and allowing for the subsequent stages of the life cycle (gate-grave). The former will require estimation of land-use changes [40,119]. If food consumption is constant, food production displaced by energy crops will be replaced by imports so that any net environmental gain will be reduced. Such displacement effects need to be identified and their environmental consequences included in a holistic assessment of land use for energy and other functions [40] along with the net energy yield associated with the land uses. This net energy yield is needed to estimate the avoided GHG emissions and other impacts from alternative energy sources, since energy crops displace other types of energy, mainly fossil-based.

Overall, this work demonstrates that the analysis of the economic and environmental impacts of different land uses is essential for sustainability policy. Given the diversity of impacts involved, it leads inevitably to the conclusion that some form of structured political decision process that includes a multitude of considerations, such as Multi-Criteria Decision Analysis, will be helpful.

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