Landscape Ecol (2019) 34:1503–1524
https://doi.org/10.1007/s10980-018-0752-7

RESEARCH ARTICLE

Ecosystem services as the products of land system dynamics: lessons from a longitudinal study of coupled human–environment systems

Richard Aspinall · Michele Staiano

Received: 23 March 2018 / Accepted: 16 November 2018 / Published online: 23 November 2018

Abstract

Context We address understanding of whole-system and landscape-based approaches to the ecosystem services framework by considering the supply of provisioning services and the dynamics of agricultural land use in Scotland between 1940 and 2016.

Objectives To characterise and understand the dynamics of change in provisioning services from agriculture in Scotland over the period 1940–2016. To identify ways in which funds of capitals and flows of inputs and output ecosystem goods are linked to land management practices and policies at a national scale.

Methods Data describing agricultural land use, production, financial and energy inputs and outputs, and drivers of change in land use in Scotland are analysed with an accounting framework that links funds of natural, human, physical and financial capital, with flows of goods and services. Flow–fund ratios are used as benchmarks of system performance and dynamics.

Results Scotland's agriculture has modernised since 1940 and become more efficient in conversion of resources, with a consequent increase in delivery of provisioning goods and services. Although the energy ratio, and flow of goods per unit hectare and per unit labour have increased, the inputs necessary to maintain those flows of ecosystem goods are also increasing, even as their relative economic costs decrease. Increases in use of fertiliser suggests that production from the soil, as a natural capital fund, is not being conserved without a large, and increasing, input. Analysis of the complexity of the coupled agricultural land system also suggests that land management rather than biodiversity is a necessary subject for evaluation of provisioning services from agriculture. Understanding of ecosystem services based on accounts that integrate inputs, outputs and flows from funds of natural, human, social, financial and physical capitals, provides a process-based foundation for improved understanding of ecosystem services and human–environmental relationships.

Conclusions Adopting an accounting approach for understanding the role of agricultural land use for supply of provisioning services, and particularly examining a long time-series of accounts, enables understanding of land changes and underlying drivers, as well as the contribution of cultural and other aspects of human systems coupled with environment systems. Accounting for ecosystem services using costs as well as benefits, and use of metrics beyond financial benefit, supports debate and evaluation of trade-offs

R. Aspinall (✉)
James Hutton Institute, Craigiebuckler, Aberdeen, Scotland, UK
e-mail: rjaspinall10@gmail.com

M. Staiano
Statistics Technology and Analysis of Data, Department of Industrial Engineering, University of Naples Federico II, 80125 Naples, Italy
e-mail: mstaiano@unina.it

between services and has direct relevance for decision- and policy-making.

Keywords Land system · Coupled human–environment system · Sustainability accounting · Scotland · Agriculture · Provisioning services

Introduction

Land use and the land systems associated with land uses present fundamental challenges for science that supports understanding of land systems, and the dynamics, management and productivity of land (Turner et al. 2007). Land use traditionally is understood as a variety of land activities (e.g. agriculture, forestry, recreation, etc.), that manage land and other resources to gain economic advantage. Land use, however, also represents a system of human–environment relations (Turner et al. 2007), and, as a coupled system (Aspinall and Staiano 2017), requires a broader definition than a list of separate land uses or land covers. In such a wider and more inclusive systems representation of land, land use and land cover are among the more obvious manifestations of human–environment relationships (Bürgi et al. 2017), yet land management, decision making, policy, and, importantly, ecosystem services, are all fundamentally linked within the same system (Foley et al. 2005, 2011; Turner et al. 2007; Angus et al. 2009; Beddington 2010; Ellis 2013; Aspinall and Staiano 2017).

Although ecosystem assessment, as a process of inventory of ecosystem services (Millennium Ecosystem Assessment 2005; UK National Ecosystem Assessment 2011), has typically framed analysis around the importance of healthy ecological and environmental systems and the central role of biodiversity (Mace et al. 2011), ecosystem services also enter the conceptual framing of land as a coupled human–environment system as fluxes from natural capital to the human system via land management and other socio-ecological drivers and processes (Baron et al. 2002; Global Land Project 2005; Levin 2006; Carpenter et al. 2009; Giampietro et al. 2009; Gleick and Palaniappan 2010; Mayer et al. 2016; Aspinall and Staiano 2017). Recent research on the conceptual framing of ecosystem services by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) identifies the importance of cultural factors and understanding in linkages between people and environment in relation to ecosystem services (Díaz et al. 2018).

In these contexts, a more explicit understanding of the mechanisms by which dynamics of human and environment systems lead to ecosystem services is necessary (Mayer et al. 2016). This requires improved understanding of relationships between land systems, land management, and ecosystem services, and identification of practical management and policy tools for improved resource management and sustainability (Bettencourt and Kaur 2011; Fish et al. 2014; Mayer et al. 2016). Landscape ecology, and other interdisciplinary approaches to sustainability, offer conceptual and analytical tools that contribute to understanding and measurement of spatial and temporal scaling; analysis of multi-level (Verburg et al. 2008), cross-scale and multi-scale influences in land systems (Tian et al. 2015), and explicit whole system perspectives (Mayer et al. 2016) that couple natural and human systems.

Part of the challenge of developing a coherent understanding of coupled natural and human systems arises from the diversity of 'ecosystem approaches'. Figure 1 indicates relationships between the main forms of ecosystem approach. The work in this paper falls within the scope of quantitative description of ecosystem services to inform ecosystem assessment, and helps to understand the roles of land management and other human action in the delivery of ecosystem services (Díaz et al. 2018).

In this paper, we use a detailed annual record, from 1940 to 2016, of ecosystem services and land systems in Scotland, focussing on provisioning services from agriculture. These data (for 1940–2010) were used in the Scotland assessment (Aspinall et al. 2011) that was part of the UK National Ecosystem Assessment (2011). In the UK NEA the data were evaluated within a conceptual framework that defined ecosystem services as predominantly derived from biodiversity (Mace et al. 2011). The delivery of provisioning services in high-input and industrialised land uses is, however, largely independent of biodiversity (Pimentel and Pimentel 1979; Pimentel et al. 1990), and indeed, typically has been achieved with considerable associated damage to biodiversity (Vitousek et al. 1997; Benton et al. 2002; Foley et al. 2005;

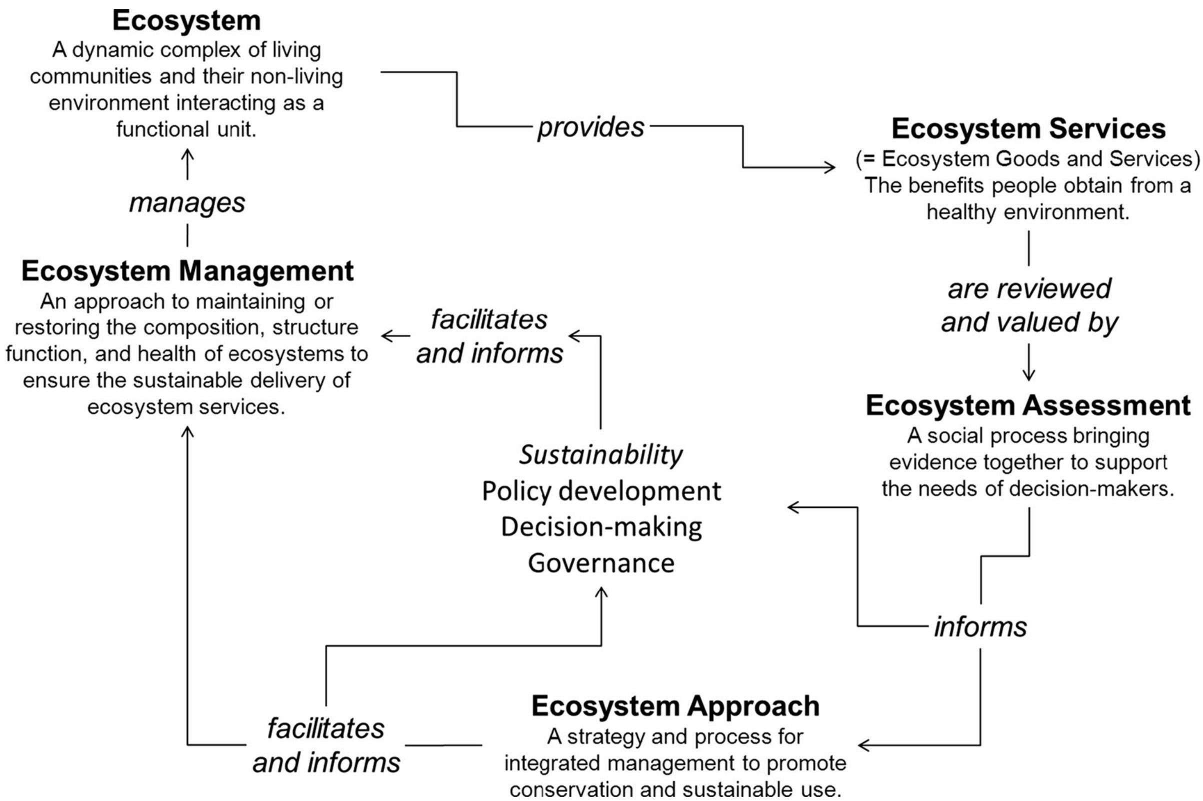

Fig. 1 Relationships between various approaches and assessments for ecosystems

Massimino et al. 2015). In the analysis we present here we interpret the data on provisioning services from agriculture as a description of land system dynamics over the last 76 years, adopting an accounting approach for sustainability assessment (Giampietro et al. 2014). This approach to sustainability accounting extends environmental economic accounting (United Nations 2014), to include not only environment, as natural capital (Hein et al. 2015; Vargas et al. 2018), but also human and physical capital funds, to assess the coupled human–environment system. Although the approach of Giampietro et al. (2014) is also designed to address sustainability at multiple scales, we address only a national scale in this paper, using an annual time step. The long time-series of annual data allows us to highlight the dynamics of change over time in the supply of provisioning services by agriculture, providing benchmarks for system performance that can be used to evaluate the nature of supply of provisioning services at other spatial and temporal scales (Foley et al. 2005; Metzger et al. 2006; Lowe et al. 2009; Fish et al. 2014).

The approach adopted treats land use, livestock number, labour (human capital), and physical capital as funds from which flows of goods are derived. The flows are provisioning services from agriculture (Millennium Ecosystem Assessment 2005; UK National Ecosystem Assessment 2011). Analysing annual data over the 76-year period reveals the impacts of year to year changes in the funds on flows of ecosystem goods, as well as the dynamic responses of the whole land system to changes in the underlying drivers of change (e.g. policy, technological innovation). By interpreting the dynamics of agricultural provisioning against a framework of land system changes, we demonstrate that the complex interactions of land systems as coupled human–environments produce ecosystem services through a variety of mechanisms beyond biodiversity, principally via land management, decision making, and policy and technological change that occur at a range of scales, including national, European and global. These are all familiar drivers of change in land systems science

(Lambin et al. 2003; Lambin and Geist 2006; Bürgi et al. 2017).

Material

Annual data for agricultural land use, livestock numbers, and labour from 1940 to 2016 were extracted from the annual series of Agricultural (June) Census records, including 1940–1978: Agricultural Statistics 1940–1978 editions, 1979:1981: Economic Report on Scottish Agriculture, 1981–2016: Abstract of Scottish Agricultural Statistics (Rural and Environment Research and Analysis Directorate 1939–present; Marshall 1946; Department of Agriculture for Scotland 1948, 1950). The annual financial inputs (costs) and outputs (benefits) and the total production and uses of crop and livestock goods from farming in Scotland for 1940 to present were extracted from the series of summaries published in the annual Economic Reports for Scottish Agriculture (see (Department of Agriculture and Fisheries for Scotland 1984; Department of Agriculture for Scotland 1950; Rural and Environment Science and Analytical Services 2016). Data for energy use in agriculture for each year from 1940 to present were from the annual series 'Digest of UK Energy Statistics' (Department for Energy and Climate Change 2010). Annual data for quantities of pesticides (SASA 2009) and fertilisers (Cooke 1982; The British Survey of Fertiliser Practice 2017), including nitrogen, potash, potassium and lime, were used as measures of pesticide and fertiliser input to farming. Technological changes over time are measured using the number and horsepower of tractors available for farming. Data on tractor numbers and HP for 1940 to present are from the series of Agricultural (December) Census records (Scottish Government 2017).

Methods

Data summary

Annual data from 1940 to 2016 and non-overlapping five-year means were calculated for areas of land in different agricultural use, livestock—measured both as number of head and livestock units (Coppock 1976), tonnes of production, labour, and financial inputs and outputs. Energy use and production in agriculture was calculated from economic data and energy data using the methods described by Leach (1976). Leach's method for energy analysis includes assessing the total energy expended, including both the direct and indirect energy used. This includes, for example, the energy consumed (i) directly for tillage and transportation and (ii) indirectly by consumption of fertilizers and pesticides, as well as production of machinery across its production-delivery chain and lifetime. Additionally, the land used for agriculture provides the system boundary for this energy analysis, the accounting recording all inputs and outputs (Leach 1976). Annual values and non-overlapping five-year means for energy inputs and outputs were used for analysis. Use of energy as a metric allows direct comparison of different inputs and outputs, and also facilitates understanding of the value of agricultural goods as food and land management actions (including fertilisers, pesticides, machinery use, and others) (Middleton 1923; Stamp 1958; Leach 1976; Bayliss-Smith 1982). To allow direct comparison of economic values over the whole time period, annual economic values for inputs and outputs were computed to 2010 equivalent value using deflators calculated from Retail Price Index (Office for National Statistics 2017).

Accounting

We adopt the rationale of a resource accounting framework (Giampietro et al. 2014), using biophysical and economic flow–fund accounts applied simultaneously, to make operational a conceptual model of the agricultural land system as a coupled human–environment system (Aspinall and Staiano 2017). The coupled system integrates natural, social, human, physical, and financial capital funds together with fluxes (flows) from these funds (Georgescu-Roegen 1975). The accounting framework similarly uses measures of funds and flows, as well as flow–fund and flow–flow ratios, as a diagnostic tool for understanding the system dynamics (Giampietro et al. 2014).

In the conceptual model, land use and land cover are incorporated as elements of the human and environment system respectively, while drivers of change and associated processes that influence land use, land cover, and land system dynamics are incorporated within a set of interacting sub-systems.

The model includes definition of both (i) driving sub-systems as a set of capital funds connected by flows and changes in the state of funds, and (ii) how these funds and flows are influenced by linkages between processes in the human (socio-economic) and environment systems and sub-systems within each.

Funds

For accounting, funds are the structural elements of the coupled human–environment system that do not change during the time interval of analysis (annual), and represent what the system is and what the system is made of (Giampietro et al. 2014). In the accounting framework used here, the funds are environment (natural capital), human capital, and physical capital. The natural capital fund is represented by the total areas of land used for various purposes within agriculture, the human capital fund by the size of the labour force working in agriculture, and the physical capital by the total number, and estimated total horsepower, of tractors available. The size of the labour capital fund is measured using the number of employees as Full-time Labour Equivalent (FLE). This is calculated as the sum of the number of full-time workers plus half the total of part-time and casual. The standard working hours for agriculture has changed over the period of this study, being about 48 h per week in the 1950s (Ministry of Agriculture 1967), 40.7 h per week in the 1980s and 1990s (Department of Agriculture and Fisheries for Scotland 1985; Rural and Environment Research and Analysis Directorate 2009) and 39 h by the 2010s (Rural and Environment Science and Analytical Services 2016). We have compiled the time series for the labour fund using published data on number of employees, and without adjustment for working hours for two reasons. First, given the large reduction in the workforce over the period cover by the study, adjusting for hours worked gives a result that is only 2% different than use of FLE without adjustment. Second, we are primarily concerned with productivity per person employed, rather than per hour worked.

Flows

Flow elements are elements of the system that are either produced or consumed during the operation of the system over the time interval of analysis (Giampietro et al. 2014). Flows reflect what the system does, as well as the inputs received from, and outputs provided to, the components of the coupled human–environment system. Flows in the accounting framework used here are inputs and outputs of energy, money, goods and materials. This includes ecosystem goods, specifically as flows of agricultural outputs as provisioning services.

Flow–fund ratios

Economic input and output flows, measured as financial totals, are compared with the land and human funds as flow–fund ratios. Similarly, flows of material inputs of fertilisers, and energy inputs and outputs, provide metrics of flows into and out of agriculture, and, again, can be used to calculate flow–fund ratios against land, human and physical funds. Production of agricultural goods and their end uses are measured as yield (tonnes per hectare and per FLE), value (£ per hectare and per FLE), and energy (joules per hectare and per FLE) (Leach 1976). Comparison of inputs and outputs through flow–flow ratios establish patterns of change in returns on investments and contribute to understanding of system metabolism.

Eight flow–fund and flow–flow ratios are used to characterise the system:

i. Crop yield. This measures production from the land fund (tonnes/ha)
ii. Food production yield from workforce (labour fund): (tonnes/FLE)
iii. Economic intensity of investment in, and return from, the land fund (£000/ha)
iv. Food production (output) density from, and resource use density (input) to, land fund (GJ/ha)
v. Economic intensity of investment in, and return from, labour fund (£000 s/FLE)
vi. Production (output) density from, and resource use density (input) through labour fund (GJ/FLE)
vii. Food production conversion efficiency of agriculture as conversion of finance to energy (GJ energy output/£000 input)
viii. Economic return on resource use by farming (£000 output value/GJ energy input)

This accounting framework for the coupled land system is directly analogous to accounting frameworks used in financial management. Financial capital funds provide a flow each year, this annual return from the capital being available for expenditure both (a) to maintain the value of the capital fund and (b) to invest in other ways. By analogy, in accounting for provisioning ecosystem services derived from farming, as a coupled human–environment land system, the various land management practices as input flows of matter, energy and work, produce goods from the land that are the flow of provisioning goods from agriculture. This return is based on the natural capital, the human capital, and the flows (Giampietro et al. 2014).

The resource accounting framework provides a mechanism for description and understanding of system dynamics (Giampietro et al. 2009; Giampietro et al. 2014), and an ability to consider the simultaneous use of different types of fund and flow variables and measures (Giampietro and Bukkens 2014). In addition to being used as a diagnostic tool, the accounting framework can also be used as for a whole systems sustainability assessment (Giampietro et al. 2014). In this case, the feasibility (measured against external constraints on the system) and viability (measured against the internal constraints of the system of the operation and dynamics of the system are assessed, including the role of human and other impacts on environment systems (Giampietro et al. 2009; Giampietro 2018). For a coupled system to be sustainable, the funds—particularly the natural capital—must be maintained, after the flows of ecosystem goods have been harvested for a given year, in a state that is at least sufficient to produce the flows that are required in the subsequent year (Giampietro et al. 2014). For the analysis here, use of fertilisers is considered as a measure of the amount of nutrients returned to the environment to maintain the productive capacity of the environment fund (primarily the soil, in the case of natural capital for agriculture).

The time interval for the accounts is annual. Because our interest is in the dynamics of the land system over time, and the analysis is for the period from 1940 to 2016, the vast majority of results are shown as time series plots. Besides, a comparison between two quinquennia is performed and the changes highlighted by means of multiple-metrics Sankey diagrams.

Results

Scotland generates a variety of crop and livestock production from arable and grazing systems that, together, use about 75% of the land area (Aspinall et al. 2011). Figure 2 shows some of the structural and technological drivers that have influenced agriculture and land use in Scotland since the 1940s, leading to a pattern of intensification that is representative of large parts of Europe. National and international policies, included in the upper part of Fig. 2, are a strong driver of land use change in agriculture (Angus et al. 2009). Four periods of different policy are shown since 1940, all influencing farming and production through financial payments. A system of Deficiency payments applied from 1947 until 1973, as a scheme to guarantee and provide stability to prices and markets and encourage food production from the UK's own resources (Angus et al. 2009). This policy was replaced when the UK joined the European Common Market and entered the Common Agricultural Policy. Initially payments were focussed on product support through prices; this encouraged modernisation of farms, partly tied to increasing farm size, and also increased production. In 1992, the McSharry Reforms moved from a system of product support through prices to a policy that focussed on producer support through income support and direct payments. Set-aside was also a characteristic of this period. The period since the mid-1990s also saw increasing attention and policy signals directed at both rural development and production. This lead to Agenda 2000 in 1999 and further reforms in 2008 that consolidated the shift to income support, introducing a single payment scheme that is both (i) decoupled from particular products and (ii) with 'cross compliance', which links payments to food safety, environmental protection and animal health and welfare standards (European Commission 2012).

The decline in number and use of horses in agriculture and trends in the number of tractors available in Scottish farming (plot in the middle of Fig. 2) show the well-known patterns of a rapid increase in mechanisation since the 1940s (Olmstead and Rhode 2001). Similarly, the increased use of inorganic nitrogen fertilisers since the 1950s (lower plot in Fig. 2) also follows a pattern repeated elsewhere. These drivers, through their legislative basis and market signals, give context to farm-scale

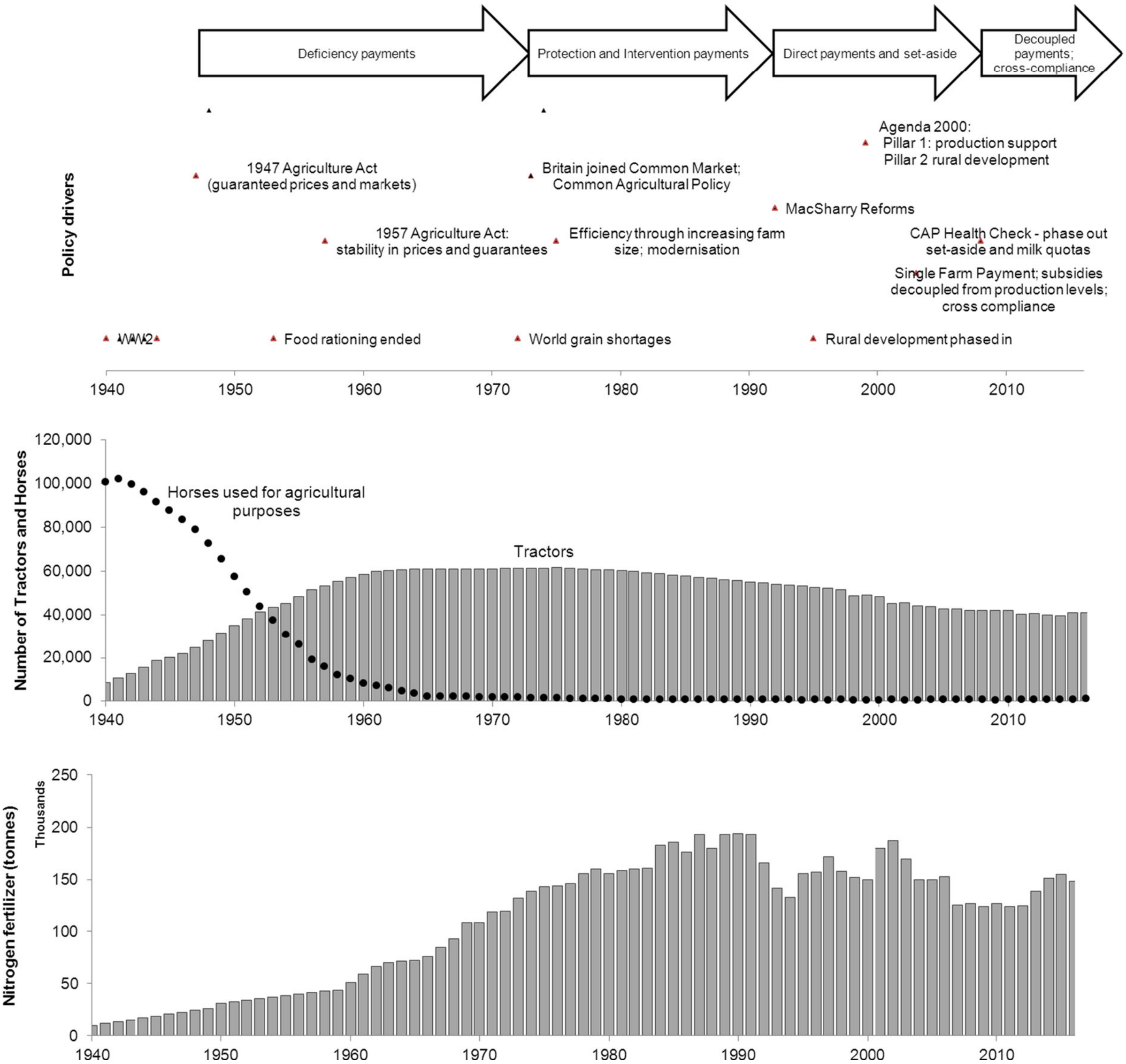

Fig. 2 Structural changes to agriculture in Scotland 1940–2016: policy drivers, mechanisation, and inorganic nitrogen fertilisers

decision making and have led to changes in agricultural practices, systems and land use. Climate change is also a factor that drives change in agriculture in Scotland (Brown et al. 2008). These changes in policy, technology, demographics and society and the intensification of agriculture have been damaging to biodiversity in Scotland (Benton et al. 2002; Hancock and Wilson 2003; Perkins et al. 2008a; Watson et al. 2009; Phalan et al. 2014).

Figures 3 shows the results for funds, Figs. 4 and 5 show the results for flows and associated funds, and Fig. 6 shows flow–fund ratios results, for annual data from 1940 to 2016.

Funds: land, livestock, labour, and physical capitals

Figure 3 shows changes in agricultural funds from 1940 to 2016, viz. land use, livestock numbers (measured as livestock units), farming labour, and tractors (via their estimated total HP). The latter figure about mechanisation is articulated in the previous Fig. 2, where the number of tractors is

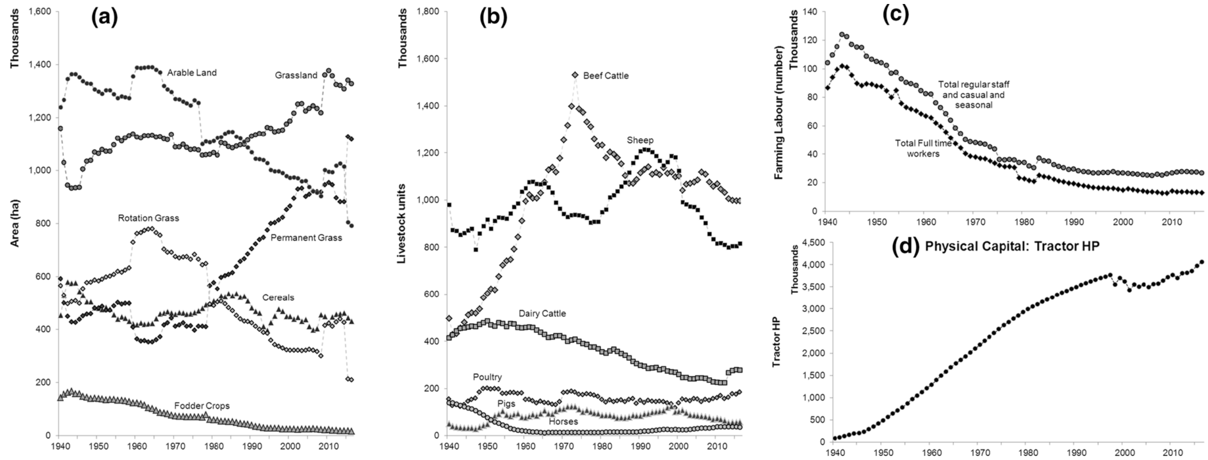

Fig. 3 Fund data: changes in the funds of **a** agricultural land use, **b** agricultural livestock, **c** human capital (farming labour) and **d** physical capital (total Tractor HP) for agriculture in Scotland, 1940–2016

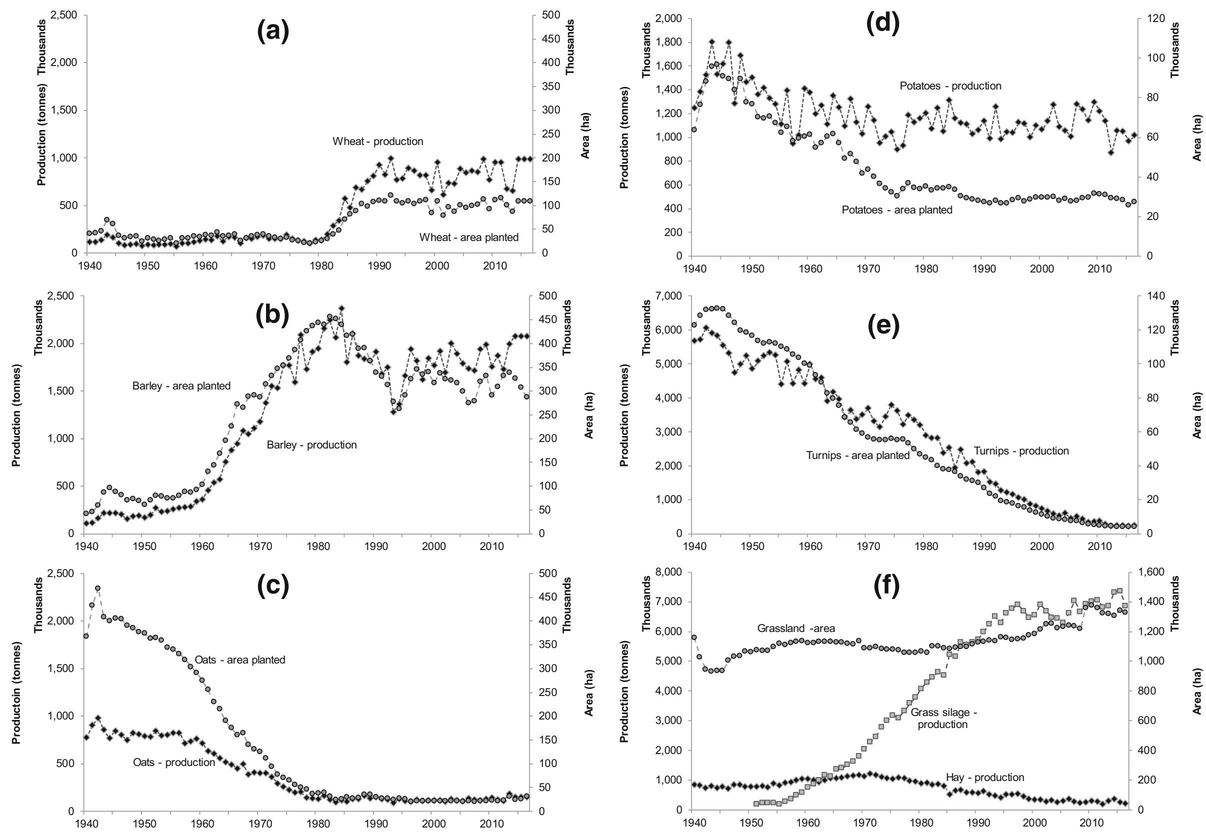

Fig. 4 Flow data: annual flows of production and funds of crops for **a** wheat, **b** barley, **c** oats, **d** potatoes, **e** turnips, and **f** grassland, hay and grass silage from agriculture in Scotland, 1940–2016

plotted together with the number of agricultural horses. Although these results are necessarily presented as a time series, the accounting framework used treats each of these variables as a fund variable that is fixed for the duration of the (annual) accounting period. Obviously funds have not been static over

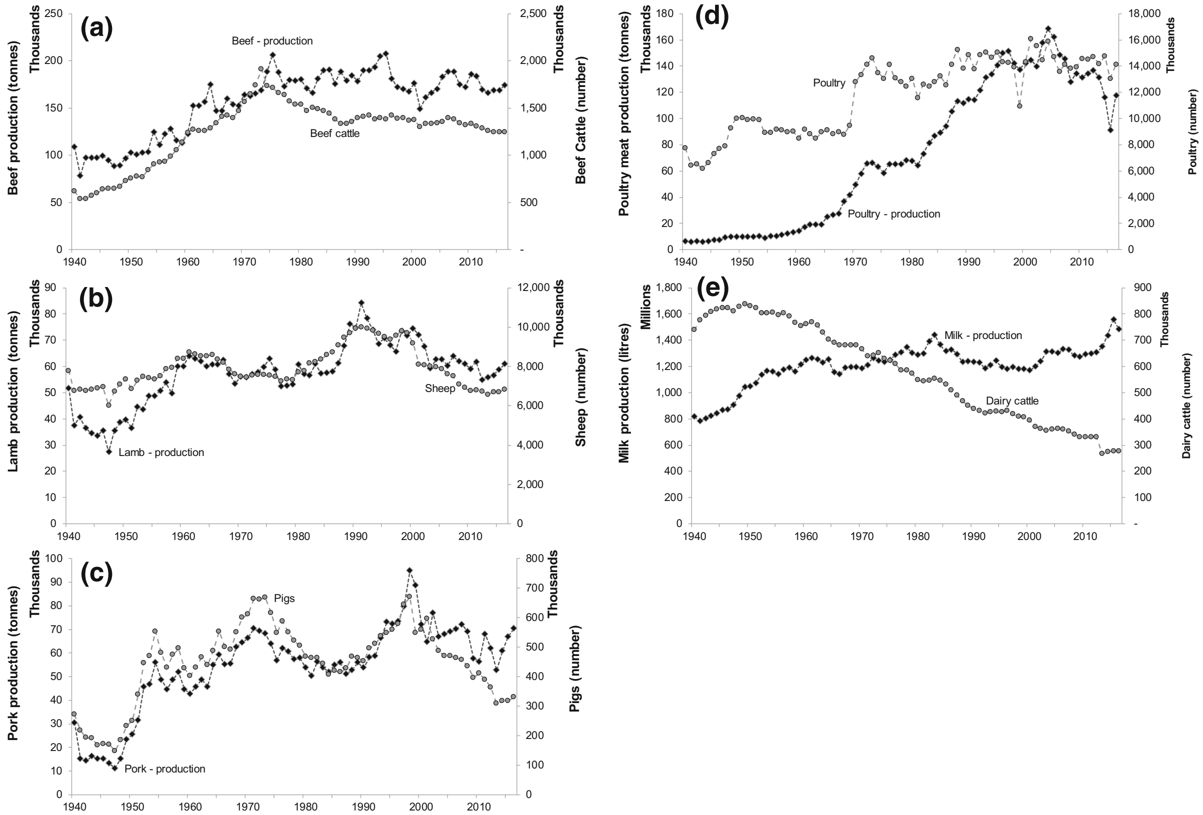

Fig. 5 Flow data: annual flows of production and funds of livestock number for **a** beef cattle, **b** sheep, **c** pigs, **d** poultry and **e** dairy cattle from agriculture in Scotland, 1940–2016

time, and changes from year to year reflect the dynamics of change in the coupled land system (Aspinall and Staiano 2017).

Land

The area of arable land in Scotland was about 1.3 million ha in the 1940s and had fallen to just under 1 million ha by 2010 (Fig. 3a). The area of agricultural improved grasslands in Scotland has varied between about 950,000 and 1.3 million ha since 1940 (Fig. 3a). The decline in area of grassland between 1940 and 1945 was associated with wartime ploughing to increase domestic crop production. Following 1945 the area of improved grassland has stayed relatively constant. Despite this, the split between permanent grassland and rotation grassland shows contrasting trends. Permanent grassland increased from between 400,000 and 600,000 ha during the period from the 1940s to 1970s, to about 900,000 ha in the 2000s, and has increased further in the last decade. Conversely, rotation grassland declined from a maximum area of almost 800,000 ha in the 1960s to under 400,000 ha in the 2000s. The abrupt breaks in the trends for permanent and rotation grassland in Fig. 3a represents a change in census methodology in 1959 when the distinction between permanent and rotation grass was altered, and a question about age of grassland was included the June agricultural survey in Scotland (Coppock 1976). Prior to 1959 these were distinguished as permanent grass, which was rarely or never ploughed and which was not counted as part of arable land, and temporary (or rotation) grass which was part of agricultural rotations. From 1959 new definitions were used for agricultural grassland (Department of Agriculture and Fisheries for Scotland 1962): grassland of 7 years old and over (treated as equivalent to permanent grass) and grass under 7 years old (treated as equivalent to temporary or rotation grass). This change resulted in some grassland being moved from

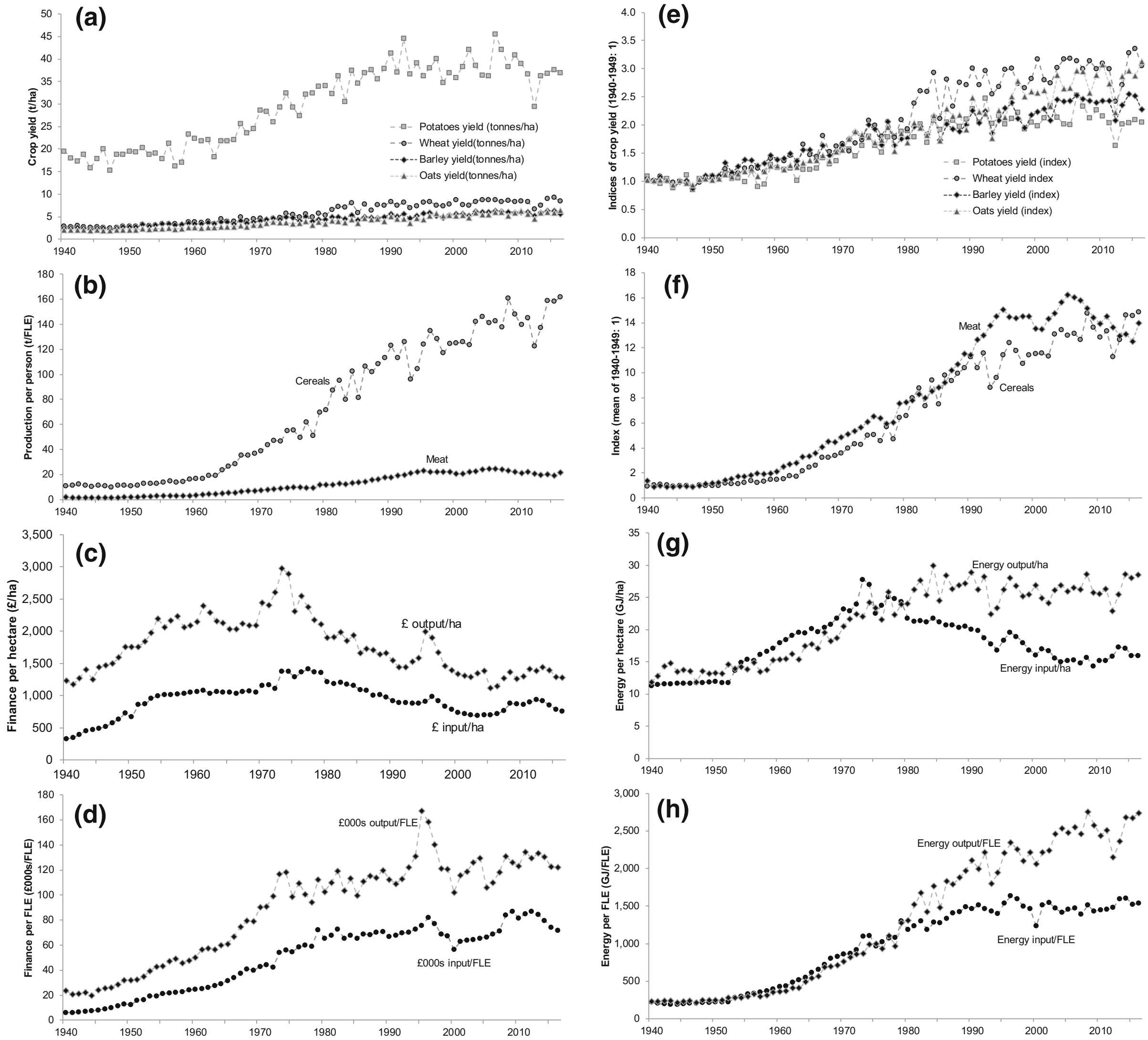

Fig. 6 Flow–fund ratios: **a** crop yields, **b** food production yield for workforce (cereals and meat production) (t/FLE), **c** economic input and output intensity (£/ha), **d** economic intensity of investment and return for labour (£/FLE), **e** indices of crop yields, **f** indices for food production conversion efficiency, **g** food production density (output) and resource use density (input) for land fund (GJ/ha), **h** production output density (output) and resource use density (input) through labour (human fund) (GJ/FLE)

permanent to temporary (Coppock 1971). Later, in 1978, these categories were redefined to grass of 5 years and over and grass of less than 5 years; the change is apparent in Fig. 3a in a second abrupt break in the plots for permanent and rotation grassland in 1979.

The area of cereals has declined slowly since 1940, although remaining between 400 and 500 thousand hectares. The proportion of arable land used for cereals was about 40% during the 1940s, falling to about one-third during the 1960s, and increasing to about 50% by 2010. The changes in composition of cereal cropland is described below.

The area of fodder crops has declined from almost 200 thousand hectares in the 1940s to about 20,000 ha by the end of the 2000s. Similarly, the proportion of arable land used for fodder crops has fallen from about 11% in the1940s to about 2% by 2010. This continues a long-term decline in growth of fodder crops on arable land in Scotland, from about 20% in the 19th century (Ministry of Agriculture 1967). The decline in the area of fodder crops in the last 70 years reflects increased specialisation in farming, the increasing use of inorganic fertilisers that reduce the reliance on both crop rotations and livestock to maintain fertility of agricultural soils, and increased use of stock feed from silage and purchased from other sources, with changing methods of livestock production. Since 2000, fodder crops have accounted for 0.5% of the financial value of agricultural output, a reduction from 2.6% in the 1950 s.

Livestock

The annual fund of livestock, measured as livestock units (Coppock 1976) in Scotland from 1940 to 2016 is shown in Fig. 3b (head counts for livestock are shown in Fig. 5). Cattle increased from the 1940s to the mid-1970s, decreasing since. Similarly, numbers of beef cattle increased from about half a million in the 1940s to about 2 million by 1973 and fell since to just over 1 million in the 2000s. The abrupt break in the graph in 1973–1974 for all cattle and beef cattle is due to a change in allocation of cattle under 1 year old within the census. The decline in the size of the dairy herd since the 1950s is clearly apparent, from over 800,000 cattle in the 1950s to about 300,000 cattle since 2000. The number of sheep has fluctuated widely, between about 5 million in the 1940s and almost 10 million throughout the 1990s. Changes reflect both severe weather (e.g. the decline associated with the severe winter of 1946–1947), and responses to policy (e.g. the increases of the 1980s associated with introduction of headage payments) (SAC 2008; Thomson 2011). The number of pigs varied between about 150,000 in the 1940s to almost 700,000 in the 1970s and 1990s. Poultry numbers increased from between 6 and 8 million during the 1940s to about 9–10 million in the 1950s and 1960s. The Agricultural Census records a rapid expansion in the poultry flock in 1970 (Department of Agriculture and Fisheries for Scotland 1971). Since the 1970s, poultry numbers have remained between 11.5 and 16 million. The decline in horses since the 1940s (and earlier) is well known.

Labour

The agricultural labour force shows a steady decline from a peak of about 140 thousand in the mid-1940s, to about 25 thousand since 2000 (Fig. 3c). This decline is mainly in full-time employees.

Physical capital

Figure 2 shows the number of horses in agricultural use, as well as the number of tractors and Fig. 3d supplies an estimate of the total available horsepower too. The trends in this graph follow the well-known pattern of a rapid increase in mechanisation since the 1940s. Although the number of tractors reached a peak in the 1960s and has declined since, the increasing power of tractors over time means that the total HP available in the tractor fleet has continued to increase throughout the entire period up to 2016 (Fig. 3d).

Flows: provisioning services—goods from agriculture

Figure 4 shows the annual production of wheat, barley, oats, potatoes, turnips and grassland, with the areas planted under each crop. Figure 5 shows the annual production of beef, lamb, pork, poultry meat (tonnes) and milk (litres) with the number of beef cattle, sheep, pig, poultry and dairy cattle between 1940 and 2016. Figure 6 shows the yield (tonnes/ha) for wheat, barley, oats and potatoes, in Scotland from 1940 to 2016.

Crops

Several major changes are apparent in the record of the land use funds and production of crops (Fig. 4). First, there has been a decline in the area of each of oats, potatoes and turnips planted since the 1940s. Second, as the area of oats has declined there has been an increase in the area of barley, to a peak in 1980. Third, there has been an increase in the area of wheat since the 1980s, largely on land previously used for barley. These changes are associated with (i) rapid mechanisation of agriculture since the 1940 and (ii) a corresponding decline in the number of agricultural horses as mechanisation replaced horses with tractors for farm work (Fig. 2b); (iii) improvements in yields for cereals through breeding and introduction of improved varieties that are productive under a wider range of environmental conditions in Scotland (see Fig. 6a, e); (iv) changed husbandry methods, including artificial fertilisers (Fig. 2c), herbicides and pesticides; and (v) changes in policy, particularly price support for wheat and barley under the Common Agricultural Policy (CAP) in the 1980s.

Figure 6a shows the mean annual yield of wheat, barley and oats since 1940. Yields of oats have increased from an average of about 2 tonnes/ha in the 1940s to 5.5 tonnes/ha since 2000, barley yields from 2.5 tonnes/ha in the 1940s to 6 tonnes/ha since 2000, and wheat yields from 2.8 tonnes/ha in the 1940s to over 8 tonnes/ha since 2000. Yields for all three crops have increased as a result of technological changes driven by scientific research, including breeding of new varieties and changed husbandry methods. Additionally, there has been an increase in the relative proportion of winter versus spring sown barley during the last three decades. This has had a detrimental effect on wintering farmland birds (Tucker 1992; Perkins et al. 2000, 2008a, b).

The area planted with potatoes has fallen from a peak of almost 100,000 ha during the early 1940s to about 30,000 ha since 1990 (Fig. 4d). Production has not, however, declined to the same extent, as a result of increases in potato yields over time (averaged across seed, early ware, and main crop/ware potatoes) from about 20 tonnes/ha in the 1940s to between 35 and 40 tonnes/ha since 2000 (Fig. 6a). These increases in yield have compensated for the decline in area planted such that annual production has been between 1 and 1.4 million tonnes per annum since the 1950s (Fig. 4d). Potatoes contribute between 6 and 10% of the value of agricultural output in Scotland and were the leading cash crop in Scotland until the late 1960s, accounting for 6.7% of agricultural output and 36% of the output from crops in 1965 (Coppock 1976).

Crop production is a function of area planted and yield. Figure 4 shows the annual production of wheat, barley, oats, potatoes, turnips and grass (as hay and silage) for Scotland. The annual production of oats has declined from over 800,000 tonnes in the 1940s to less than 120,000 tonnes since 1980. Barley production was 10 times higher in the 2000s than it was in the 1940s (average of 176,000 tonnes in 1940s to 1.8 million tonnes in the 2000s, with a peak in the 1980s of over 2 million tonnes). Wheat increased from 117,500 tonnes in the 1940s to over 800,000 tonnes in the 2000s.

Cereals are used for human consumption, for distilling and malting, and for stock feed (DTZ 2007; Rural and Environment Research and Analysis Directorate 2010). About half of the wheat crop and 33% of the barley crop is used for distilling and malting (Rural and Environment Research and Analysis Directorate 2010). About 14% of wheat, 65% of barley, and 13% of oats are used as stock feed (1964–1972 means: wheat 47.6%; barley: 52.2%; oats: 33.7%).

Fodder crops

The decline in area of fodder crops has been noted above, but Fig. 4e shows the change in area of turnips, these historically being the main fodder crop. The area of turnip cropping has declined from about 120,000 ha in 1950 to about 5000 ha by 2010. Traditionally the turnip crop has been mostly used as part of a rotation and consumed on the farm where it is grown, being fed to sheep while still in the ground (Coppock 1976). This provides winter food for the sheep, the sheep, in turn, providing manure to support the fertility of the soils. Fodder crops are also important for conservation of arable weed and wintering farmland bird populations (Hancock and Wilson 2002, 2003).

Livestock products

Livestock are the dominant agricultural product, by value, from Scottish agriculture (Rural and Environment Science and Analytical Services 2016). In 2016, livestock contributed about 33% and livestock products (milk, milk products, eggs, wool) a further 12% of annual agricultural output by value, although this is compared with 36% and 40% respectively in 1950–1954.

Some upland vegetation is used to graze cattle and sheep, particularly during the summer months. Rough grazing and deer forest are considered in the agricultural returns for Scotland and recognised for their contribution as grazing land for livestock. However, livestock production in Scotland is most appropriately considered as an integrated system that uses upland (rough and improved) grazing as well as elements of lowland agriculture, including fodder crops and grain produced in cereal systems.

Beef production generally has increased over the last 70 years. The large decline in 2001 shows the influence of the foot-and-mouth outbreak (Fig. 5a). Beef production has the largest share of output of Scottish agriculture, at about 28% of value in 2015

(Rural and Environment Science and Analytical Services 2016).

Lamb meat production has closely followed the pattern of sheep numbers (described above) (Fig. 5b). For 2015, lamb production is about 10% of the value of agricultural output (Rural and Environment Science and Analytical Services 2016).

The production of pork shows a very similar pattern to changes in the number of pigs (Fig. 5c), with a maximum of 91,000 tonnes produced in 1998. The value of pork production in 2015 is about 3% of agricultural output (Rural and Environment Science and Analytical Services 2016).

The production of chicken meat and total number of poultry are shown in Fig. 5d. Meat production has increased from less than 20,000 tonnes per year in the 1950s and first half of the 1960s to a peak of about 160,000 tonnes in the early 2000s, since when the amount of poultry meat produced has declined to about 120,000 tonnes. Poultry comprises about 5% of value of agricultural output in 2015 (Rural and Environment Science and Analytical Services 2016).

The milk production and number of dairy cattle in Scotland from 1940 to 2016 are shown in Fig. 5e. Despite a decrease in the number of dairy cattle from the 1950s onwards, milk production increased rapidly from the 1950s to between 1200 and 1400 million litres from the 1980s, with a peak of almost 1600 million litres in 2015. Milk and milk products contribute about 14% of the value of agricultural output in 2015 (Rural and Environment Science and Analytical Services 2016).

Flow–fund ratios

Flow–fund ratios for yields (tonnes/ha) for cereals and potatoes are shown in Fig. 6a. Yield records the flow (production) against the capital fund of land (area). Figure 6b also shows the yields for cereals and potatoes scaled against the mean yield for each crop measured over the period from 1940 to 1949 (inclusive). Yields for wheat have increased from 1940s to 2016 by a factor of about 3, barley by about 2.4, oats by 2.7, and potatoes by 2.2 (Fig. 6e).

Figure 6b shows flow–fund ratios for flows of cereals and meat production against the fund of labour (as Full-time Labour Equivalents. These values are also compared with their means for 1940 to 1949 to show the magnitude of changes over time (Fig. 6f). Figure 6c, d show the financial inputs and outputs per FLE and per hectare for 1940–2016. Financial values are reported in 2010 equivalent. Figure 6g, h show the total energy input and output per FLE and per hectare for 1940–2016, respectively.

Flows of both cereals and meat production per unit labour (measured as FLE) have increased markedly from 1940 to 2016, by factors of between 12 and 16 compared with their means for 1940–1949.

Inputs and outputs of energy per FLE of labour have increased over time (Fig. 6h). Prior to 1980 the ratio of inputs and outputs was about 1, but since 1980 energy outputs per FLE have continued to increase while energy inputs per FLE have remained at about 1500 GJ/FLE, and by the 2010s the input:output ratio is about 1:1.8, with about 2600 GJ/FLE for outputs.

Inputs of energy per hectare increased from about 12 GJ/ha in 1950 to a maximum of 27 GJ/ha in 1973 and 1974, and have since declined to about 16 GJ/ha. Energy outputs per hectare increased from about 13 GJ/ha in the 1950s to about 28 GJ/ha by the mid-1980s and have remained at that level since (Fig. 6g).

Inputs and outputs of money per FLE and per hectare show a more complex pattern of change over time. Inputs and outputs of money per unit area increased from 1940 to the early 1970s, and have fallen since, particularly output per hectare of farmland (Fig. 6c). At 2010 prices, inputs per ha between 2000 and 2010 were about £755/ha and outputs £1280/ha, compared with £719/ha and £1709/ha averages for the 1940s and 1950s. In real terms, inputs have remained about the same, but output has declined to about 70% of its former value (Fig. 6c). Inputs and outputs of finance per unit labour (£/FLE) have increased over time, with a peak of output per unit labour in the mid-1990s (Fig. 6d). Inputs per person are about 5 times higher since 2000 than in the 1940s and 1950s, while outputs per person are about 4 times greater.

Funds, flows and the coupled land system

Figures 7 and 8 show the average economic inputs and outputs, the energy inputs, outputs and end-uses of agricultural products, and the land used for agriculture, with regard to the periods 1950–1954 and 2005–2009 respectively, summarising the funds of land and the related flows within the agricultural land system as a whole.

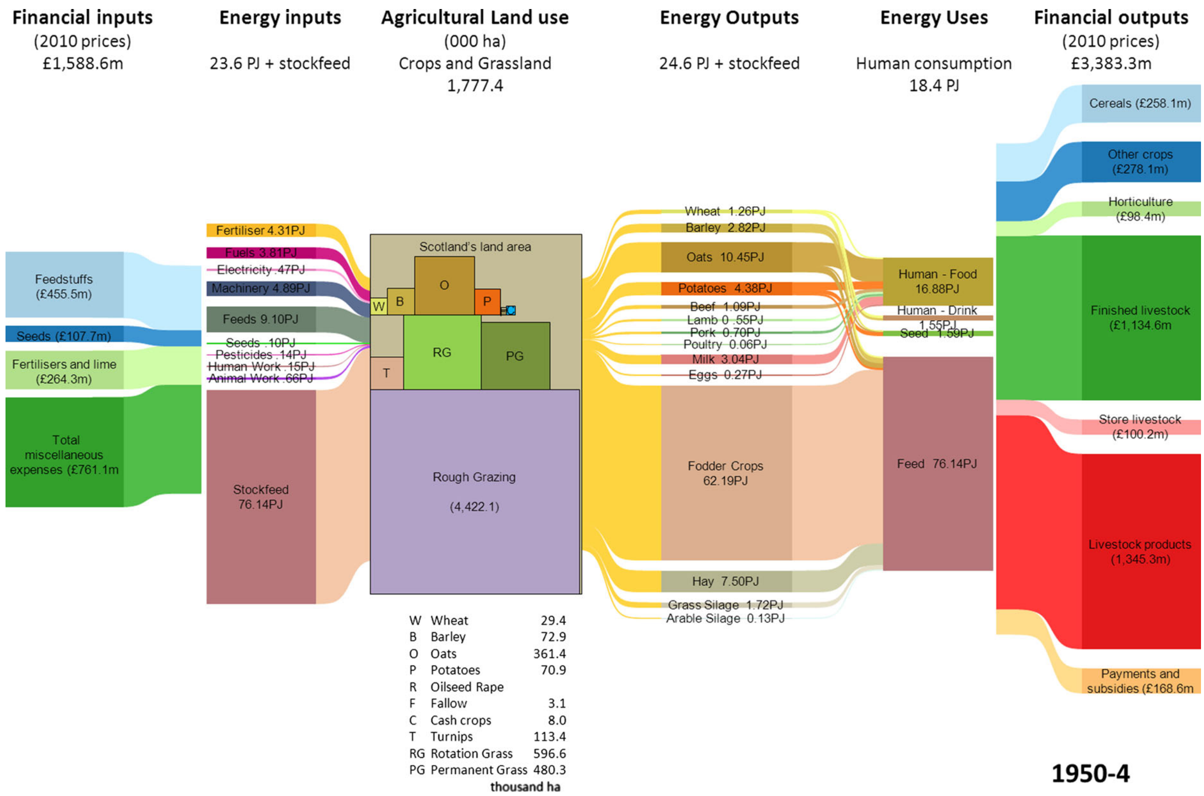

Fig. 7 Sankey diagram for financial and energy inputs and outputs through agricultural land in Scotland, 1950–1954

Although Scotland's aggregate farming system has remained a mixed arable-livestock system (Symon 1959), with dominance of the livestock sector, for the whole of the time period studied, these composite figures show some large changes within the system.

Comparing the two summaries shows increases in area for wheat and barley, oilseed rape, cash crops, fallow, and permanent grass while the total arable land remained almost the same. There are also declines in area for oats, potatoes, turnips, and rotation grassland. These changes have been described above. Comparison of inputs and outputs for finance shows a greater return on investment in 1950–1954 compared with 2005–2009, total output (£3383 m) being more than double the input (£1588 m) as opposed about 1.2 times for 2005–2009 (£2368 m for input and £2895 m for output), although return on direct operating costs, ignoring capital investment in farming, in 2005–2009 remains at about 1.9 times. Although reporting for accounts has improved over time, the financial data in the Figs. 7 and 8 also show the increased real terms value of cereals, horticulture, and payments and subsidies in 2005–2009 compared with 1950-4. Similarly, finished and store livestock, and livestock products are relatively of lower value. Fertilisers and seeds cost less in real terms in 2005–2009 than in 1950–1954 (Figs. 7, 8).

Figures 7 and 8 also summarise inputs and outputs measured as energy. Although the total energy inputs in 1950–1954 and 2005–2009 are similar (23.6 PJ and 27.9 PJ respectively), the total energy outputs are much higher in 2005–2009 than in 1950–1954 (49.5 PJ compared with 24.6 PJ). There are large increases in absolute value for wheat and barley, and large relative increases for pork, and poultry between the two periods. There is a large decrease for oats. Fodder crops and grass show the largest differences between the periods. There are large declines in absolute value for fodder crops (mainly turnips) and hay, from 62.2 PJ to about 5.0 PJ and from 7.5 to 2.8 PJ respectively. Grass and arable silage have increased however, from 1.72 to 62.4 PJ and from 0.1 to 3.6 PJ respectively. The inputs of fertiliser measured in the energy account, the energy being based on the quantity of fertiliser used,

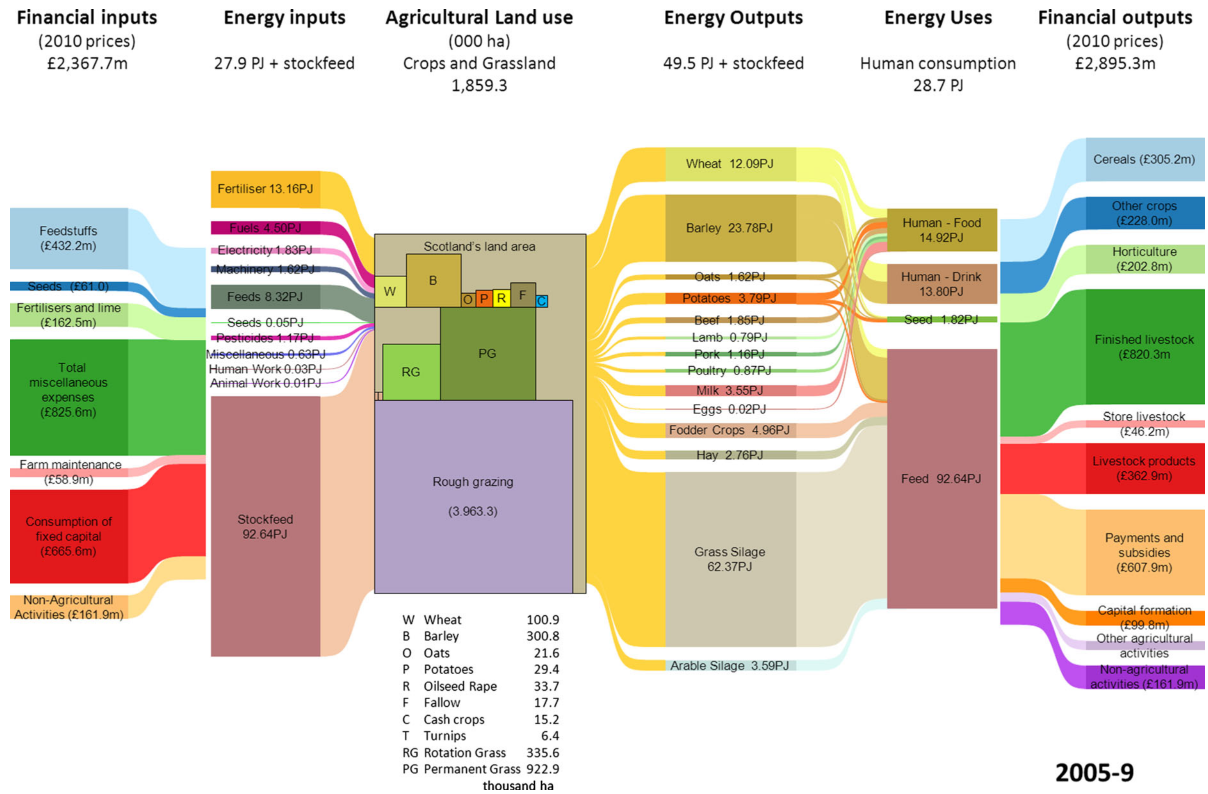

Fig. 8 Sankey diagram for financial and energy inputs and outputs through agricultural land in Scotland, 2005–2009

shows that about three times as much fertiliser is used in 2005–2009 compared with 1950–1954.

Figures 7 and 8 show the end uses of the outputs from agriculture, measured in energy units. Although the total energy content of agricultural products used for human food is similar in the two periods (16.9 PJ and 14.9 PJ respectively), the amount used for making drink, through distilling and malting, has increased by 9 times, from 1.55 PJ in 1950–1954 to 13.8 PJ in 2005–2009. The proportion of cereals used for stock-feed remains at just over 50% of production.

Figure 9a records the total financial inputs and outputs and total income from farming (2010 prices) and Fig. 9b the total energy inputs and outputs as well as the yearly balance (output-input), partly summarising the whole system analyses presented in Fig. 7 and 8 for each year in the study. Results for inputs and outputs for both finance and energy follow the same general pattern of change over time that has been described above for finance and energy flows per hectare of land.

The economic and energy conversion efficiencies, measured as the ratio of outputs to inputs or simply as their balance, show two different patterns (Fig. 9a, b). The economic efficiency of Scotland's farming system, taken as a whole, was greater, in real terms, before 1973, than since (Fig. 9a). This period of greater economic efficiency and real terms income from farming coincides with the period of deficiency payments, guaranteeing prices, that operated from 1947 until 1973 (Fig. 2a). The energy ratio shows a different pattern, with increased output to input since about 1980 than before, following modernisation of agriculture and intensification (Fig. 9b), associated with the UK entering the Common Market and Common Agricultural Policy (Fig. 2).

Figure 9c includes two overall flow–flow ratios: food production conversion efficiency of agriculture, as conversion of finance to energy (GJ energy output/£000 input), and the economic return on resource use by farming (£000 output value/GJ energy input). These two graphs combine the energy and economic output-input ratios, showing the complex changes that

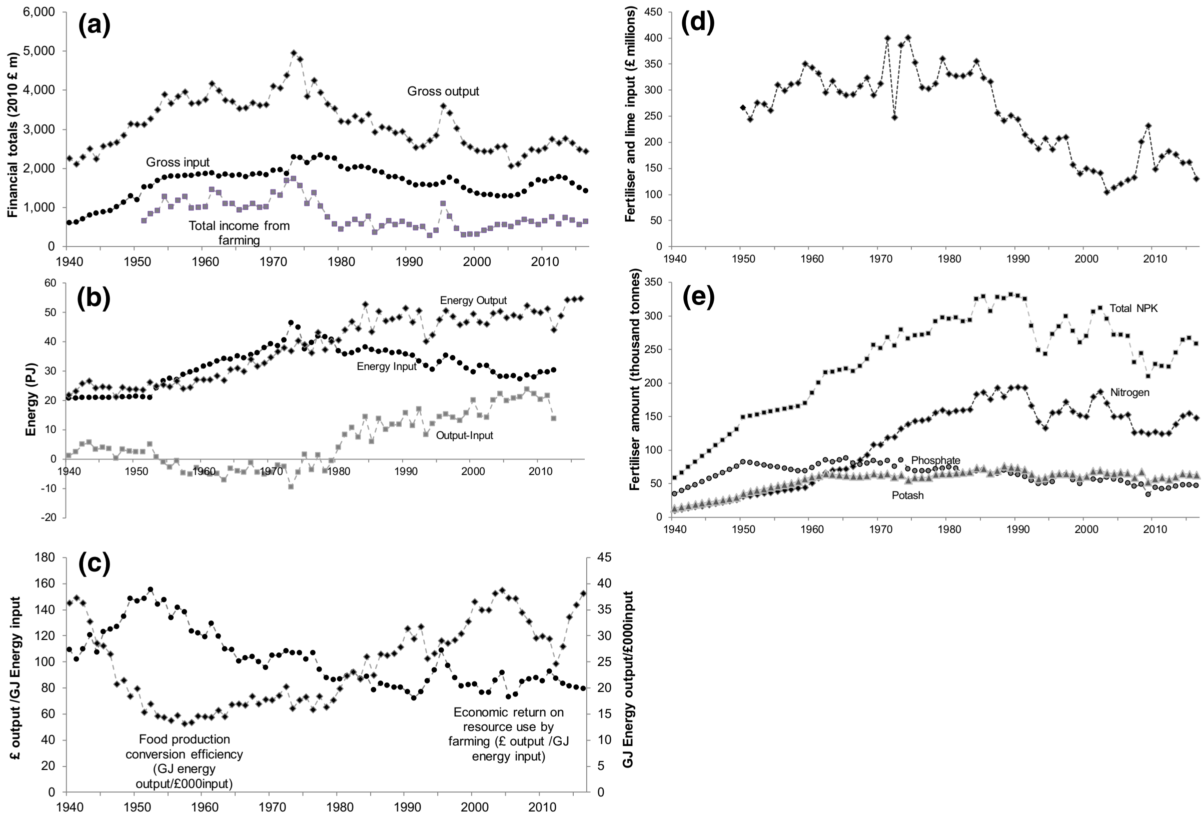

Fig. 9 Flow–flow relationships: **a** total inputs and outputs of finance, and total income from farming (2010 prices), **b** total inputs and outputs of energy, **c** Food production conversion efficiency (conversion of finance to energy, GJ energy output/£000 input) and economic return on resource use by farming (£ output/GJ energy input), **d** expenditure on fertiliser and lime inputs (2010 £millions) and **e** fertiliser inputs (kilotonne) for 1940–2016

have occurred between 1940 and 2016. The graphs reinforce the results presented in Figs. 7 and 8 for 1950–1954 and 2005–2009 respectively, placing these periods within a sequence of changes that have (i) increased flows of provisioning goods through increased production, (ii) increased the energy and resource use conversion efficiency of farming, and (iii) seen a decline in the economic efficiency and value (in real terms) of the provisioning goods produced by agriculture. These changes are directly associated with the changes in policies previously described.

Discussion

Agriculture and provisioning ecosystem services in Scotland

Although we note that aggregate statistics mask differences between types of farming and regions within Scotland, in the context of ecosystem assessment to understand the production of provisioning services from agriculture, valuation of goods and land use over time, and the changing policy context, a national scale of analysis is constructive. The evidence is that the agricultural system of Scotland has changed considerably since 1940, although remaining predominantly a mixed system within the limited agricultural capabilities of Scotland's climate and acid soils (Bibby et al. 1982; Brown et al. 2008; Rivington et al. 2013). The accounts described show the interdependence of arable and livestock systems in

Scotland, unsurprising for a mixed system. Changes in planting of cereals in Scotland over time show that although the total area planted has changed relatively little, the balance of wheat, barley and oats has changed dramatically, partly due to mechanisation, but also due to changes in policy and support mechanisms, and the technical capabilities of new varieties and land management practices. The decline in oat production now allows increased production of wheat and barley for human uses, especially for drink, and as feed for meat production (DTZ 2007; Rural and Environment Research and Analysis Directorate 2010).

The accounts for inputs and outputs measured as energy (Figs. 7, 8, 9), show that Scotland's agriculture has become more effective in conversion of resources over the last 70 years, with greater quantities of products produced per unit input (Figs. 7, 8), and compared with the capital funds of labour and land area. For labour, this is partly due to a reduction in workforce size. In contrast, the economic accounts show that although real terms costs (at 2010 prices) have generally reduced over time for inputs such as fertilisers and seeds (Figs. 7, 8), as have returns on investment, and agriculture is now less efficient in financial terms than in the past under different policy conditions. This has implications for economic valuation of ecosystem services, since financial value is not an absolute measure and consistent over time, in the way that quantity of product produced is related to potential uses.

For fertiliser, used in our accounts as a measure of the annual return that must be made in order to maintain the land and soil capital fund in a condition to support the next year's flows, the energy accounts show inputs of fertiliser to have increased by a factor of three between 1950–1954 and 2005–2009, despite the financial analysis showing real terms costs decreasing over time. This indicates that the natural capital fund of agricultural land and soils is not being conserved without a large, and increasing, input to the land system. Additionally, the greater inputs of inorganic fertiliser, as well as many other land management changes in agriculture needed to maintain productivity, have had negative impacts on both biodiversity (Perkins et al. 2008a; Watson et al. 2009; Aspinall et al. 2011) and environment.

Yields of crops have increased over time through modernisation, intensification and use of new varieties. Output per person and per hectare of land, measured as energy and production in tonnes, have also increased over time, although the economic return, measured at 2010 prices, has fallen per hectare, while increasing when measured as a flow against human capital (Fig. 6c, e, d).

These findings tell a story of agricultural intensification since 1940 resulting in greater production, and a consequent increase in agriculture's delivery of provisioning goods and services. However, the results also show that although the energy ratio, and flow of goods per unit hectare and per unit labour are increasing, the inputs necessary to maintain those flows of ecosystem goods are also increasing, even as their relative costs decrease. The financial challenges facing farming in Scotland are already well-known (SAC 2008; Scottish Government 2015; Thomson 2011) and the accounting here conforms to this understanding. In sustainability terms, the evidence in the time series of accounts for Scottish agriculture from 1940 to 2016 is that agriculture has modernised and become increasingly efficient in all of labour, energetics, and land use terms (Figs. 3, 4, 5, 6, 7, 8, 9), producing more of the goods that are now understood and valued as provisioning services from Scotland's farmed ecosystems. While doing this, however, agriculture has become less sustainable economically (Figs. 7, 8, 9), and the increase in fertilisers challenges both the feasibility (external) and viability (internal) system dimensions of sustainability of the system (Giampietro et al. 2014), placing additional burdens on natural capital (land and soil) and its capacity to deliver provisioning services.

Accounting for land systems and ecosystem services

Our accounting analysis, based on land systems as coupled natural and human systems, allows evaluation of the various processes and driving factors by which provisioning ecosystem services are realised and recovered by agriculture, increasing understanding of change and the nature of ecosystem services, including the roles of humans and societal actions in both the development and deterioration of different ecosystem services. The post-1940 record of change in agricultural provisioning services in Scotland reflects the impacts and importance of changes in inputs of human, social, physical, and financial capitals and processes, as well as natural capital and structural changes in land use within the UK, across Europe and globally. All of these changes have altered the quantity and quality of agricultural provisioning services. Our input–output accounting analysis, by analysis of both energy and finance, reveals not only changes in value of services, but also the economic and energy costs of changes in human and technological capital associated with recovering the services. Specifically, as already stated, energy ratio, as a measure of resource use efficiency, has increased markedly over time along with innovation in physical and human systems, while the relative economic value of output has fallen. The analysis of the complexity of the coupled agricultural land system also suggests that land management rather than biodiversity is the necessary subject for evaluation of provisioning services from agriculture. Since the underlying accounting model requires a metric for the maintenance of natural capital involved in agricultural production through a return to the capital fund, our analysis suggests that the natural capital fund has been maintained since 1940 by increasing inputs of fertiliser. Impacts of agricultural fertilisers in the environment are known (Wright et al. 1991; Sharpley et al. 2010), and they have negative impacts on regulating and supporting services, even as the amount and value of provisioning ecosystem services has generally increased. Trade-offs between different ecosystem services related to land use requires further study (Foley et al. 2005; de Groot 2006; Angus et al. 2009; Francis et al. 2014).

This understanding of ecosystem services that we present, based on an analysis that integrates inputs, outputs and flows of natural, human, social, financial and physical capitals, provides a process-based foundation for improved understanding of ecosystem services and human–environmental relationships. Accounting for ecosystem services using costs as well as benefits, and use of metrics beyond financial benefit, supports debate and evaluation of trade-offs between services and has direct relevance for decision- and policy-making (Blackstock et al. 2009; Nesheim et al. 2014).

Our analysis focusses on agricultural land use within Scotland. As such, it only partially accounts for externalisation and the demands that agriculture in Scotland places on land systems outside Scotland as 'virtual land use' (in the sense of virtual water (Hoekstra and Mekonnen 2012)). For example, import of feeding stuffs for animals to Scotland in 2009 was valued at £278 million (HM Revenue and Customs 2010); this input is accounted for in our method through the costs of livestock feed to agriculture, but the full environmental and energetic costs of this virtual land use are not however, accounted for here. Methods for this type of analysis are mainly based on financial costs, and neither methods nor data are sufficiently developed for use at the level of detail and for the period we present (Pretty et al. 2000).

Landscape ecology and land system dynamics

The accounting framework we use addresses a series of theoretical, methodological and operational issues associated with understanding of whole-systems and landscape-based approaches (Giampietro and Bukkens 2014) to improving application of the ecosystem services framework. Used with a conceptual framework of land systems as a coupled human–environment system (Aspinall and Staiano 2017), the whole system accounts combines theoretical approaches and empirical data with potential to advance the scope of narratives about landscape and landscape change, both as a concept and as an organising scale for elucidating and communicating policy and management impacts on ecosystem services.

Landscape ecology is central to these potential advances (Mayer et al. 2016). Our perspective, based on land as a fully coupled human–environment system, shows that the land systems producing provisioning ecosystem services can be considered as coupled human-natural systems in accounting, and that explanation of ecosystem services through a lens of biodiversity can miss the importance of cultural and other aspects of human systems coupled with environment systems (Díaz et al. 2018). Further, within a framing of land use as a coupled human-environment system, the results show that the long-term dynamics of agricultural land systems, and associated provisioning services, are a function of both environmental and societal funds and flows, and provisioning services depend on the continued integrity of this coupled system.

Ecosystem services are a key element at the interfaces of the coupled system and could be analysed as fluxes from natural capital to the human system via the land system. The coupling makes explicit the mechanisms by which dynamics of the human and environment systems lead to ecosystem services. Understanding these mechanisms draws on well-developed themes in landscape ecology, including understanding and measurement of spatial and temporal scaling, to allow analysis of cross-scale and multi-scale influences in the land system. This approach explicitly embraces a whole systems perspective.

Our analysis based on land systems more fully evaluates the processes by which ecosystem services are realised, increasing understanding of change and the nature of ecosystem services and the roles of humans and societal actions in both the development and deterioration of different ecosystem services. For example, the post-1940 record of change in agricultural provisioning services in Scotland reflects the impacts and importance of changes in inputs of human, social, physical, and financial capitals and processes, as well as natural capital and structural changes in land use within the UK, across Europe and globally. All of these changes have altered the quantity and quality of agricultural provisioning services. Our input–output accounting analysis includes analysis of energy and finance and reveals not only changes in value of services, but also the economic and energy costs of changes in human and technological capital associated with recovering the services. Specifically, energy conversion, measured as the energy ratio, has increased markedly over time along with innovation in physical and human systems, while the relative economic value of output has fallen. The analysis of the coupled system also reveals that the fund of biodiversity, and by association, natural capital, has also fallen while the amount and value of provisioning ecosystem services has generally increased.

This understanding of ecosystem services that we present, based on an analysis that integrates inputs, outputs and flows of natural, human, social, financial and physical capitals, provides a process-based foundation for improved understanding of ecosystem services and human-environmental relationships. Accounting for ecosystem services using costs as well as benefits, and use of metrics beyond financial benefit, is critical to support debate and evaluation of trade-offs between services and has direct relevance for decision- and policy-making. This all offers further directions for both landscape ecology and land systems science, including opportunities for landscape design, scenario development and creation of informative narratives, and input to policies and strategies for land use futures based on understanding the complex inter-linkages of societal and environmental capitals and flows with many other aspects of society, economy and environment.

Conclusion

The evaluation of provisioning services for 1940–2016 in Scotland using an integrated accounting method, reveals considerable underlying change over time in the farming system, even though, at an aggregate national scale, farming has remained a mixed system dominated by livestock. Changes in land use and farming operations have considerably increased the supply of provisioning services, although the accounts show that this has needed an increasing return to the natural capital fund in terms of fertiliser.

The perspective about the supply of provisioning services that we present, based on an integrated analysis of input and output flows to and from funds of natural, human, social, financial and physical capitals, provides a process-based foundation for improved understanding of ecosystem services and human-environmental systems relationships. It also allows to highlight the roles of land management in gaining ecosystem services from human uses of land and environmental capital. Accounting for ecosystem services using costs as well as benefits, and use of metrics beyond financial benefit, supports debate and evaluation of trade-offs between services and has direct relevance for decision- and policy-making.

Acknowledgements RA acknowledges financial support from University of Naples for collaboration with the STAD group based at University of Naples Federico II. MS acknowledges financial support from the European Union's Horizon 2020 research and innovation programme under grant agreement No 689669. This work reflects the authors' views only: the funding agencies are not responsible for any use that may be made of the information contained. We also acknowledge the helpful comments of the referees.

References

Angus A, Burgess PJ, Lingard J (2009) Agriculture and land use: demand for and supply of agricultural commodities, characteristics of the farming and food industries, and

implications for land use in the UK. Land Use Policy 26S:S230–S242
Aspinall RJ, Green D, Spray C, Shimmield T, Wilson J (2011) Status and changes in the UK ecosystems and their services to society: Scotland. In: UK National Ecosystem Assessment (ed) The UK National Ecosystem Assessment: technical report. UNEP-WCMC, Cambridge, pp 895–977
Aspinall R, Staiano M (2017) A conceptual model for land system dynamics as a coupled human–environment system. Land. https://doi.org/10.3390/land6040081
Baron JS, Poff NL, Angermeier PL, Dahm CN, Gleick PH, Hairston NG, Jackson RB, Johnston CA, Richter BD, Steinman AD (2002) Meeting ecological and societal needs for freshwater. Ecol Appl 12:1247–1260
Bayliss-Smith TP (1982) The ecology of agricultural systems. Cambridge University Press, Cambridge
Beddington J (2010) Food security: contributions from science to a new and greener revolution. Philos Trans R Soc B 365:61–71
Benton TG, Bryant DM, Cole L, Crick HQP (2002) Linking agricultural practice to insect and bird populations: a historical study over three decades. J Appl Ecol 39:673–687
Bettencourt LMA, Kaur J (2011) Evolution and structure of sustainability science. Proc Natl Acad Sci USA 108:19540–19545
Bibby JS, Douglas HA, Thomasson AJ, Robertson JS (1982) Land capability classification for agriculture. The Macaulay Institute for Soil Research, Aberdeen
Blackstock KL, Matthews KM, Buchan K, Miller DG, Aspinall R, Rivington M (2009) Necessary but not sufficient: tools for analysing multi-scale integrated eco-social systems. In: 18th World Imacs Congress and Modsim09 international congress on modelling and simulation: interfacing modelling and simulation with mathematical and computational sciences
Brown I, Towers W, Rivington M, Black HIJ (2008) Influence of climate change on agricultural land-use potential: adapting and updating the land capability system for Scotland. Clim Res 37:43–57
Bürgi M, Bieling C, von Hackwitz K, Kizos T, Lieskovský J, Martín MG, McCarthy S, Müller M, Palang H, Plieninger T, Printsmann A (2017) Processes and driving forces in changing cultural landscapes across Europe. Landscape Ecol 32:2097–2112
Carpenter SR, Mooney HA, Agard J, Capistrano D, DeFries RS, Diaz S, Dietz T, Duraiappah AK, Oteng-Yeboah A, Pereira HM, Perrings C, Reid WV, Sarukhan J, Scholes RJ, Whyte A (2009) Science for managing ecosystem services: beyond the Millennium Ecosystem Assessment. Proc Natl Acad Sci USA 106:1305–1312
Cooke G (1982) Fertilizing for maximum yield, 3rd edn. Granada, London
Coppock JT (1971) An agricultural geography of Great Britain. G. Bell and Sons Ltd, London
Coppock JT (1976) An agricultural atlas of Scotland. John Donald Publishers Ltd., Edinburgh
de Groot R (2006) Function-analysis and valuation as a tool to assess land use conflicts in planning for sustainable, multi-functional landscapes. Landsc Urban Plan 75:175–186
Department of Agriculture and Fisheries for Scotland (1962) Agricultural statistics. 1959 and 1960. Scotland. Department of Agriculture and Fisheries for Scotland, Edinburgh
Department of Agriculture and Fisheries for Scotland (1971) Agricultural statistics. 1970. Scotland. Department of Agriculture and Fisheries for Scotland, Edinburgh
Department of Agriculture and Fisheries for Scotland (1984) Economic report on Scottish agriculture. Department of Agriculture and Fisheries for Scotland, Edinburgh
Department of Agriculture and Fisheries for Scotland (1985) Economic report on Scottish agriculture. Department of Agriculture and Fisheries for Scotland, Edinburgh
Department of Agriculture for Scotland (1948) Agricultural statistics 1939 to 1944 for Scotland. Department of Agriculture for Scotland, Edinburgh
Department of Agriculture for Scotland (1950) Scottish agricultural economics, vol I
Department for Energy and Climate Change (2010) Digest of UK energy statistics 2010. TSO, London
Díaz S, Pascual U, Stenseke M, Martín-López B, Watson RT, Molnár Z, Hill R, Chan Kai MA, Baste IA, Brauman KA, Polasky S, Church A, Lonsdale M, Larigauderie A, Leadley PW, van Oudenhoven APE, van der Plaat F, Schröter M, Lavorel S, Aumeeruddy-Thomas Y, Bukvareva E, Davies K, Demissew S, Erpul G, Failler P, Guerra CA, Hewitt CL, Keune H, Lindley S, Shirayama Y (2018) Assessing nature's contributions to people. Science 359:270
DTZ (2007) Scottish primary food and drink produce processed in Scotland. DTZ, Edinburgh
Ellis EC (2013) Sustaining biodiversity and people in the world's anthropogenic biomes. Curr Opin Environ Sustain 5:368–372
European Commission (2012) The common agricultural policy—a story to be continued. Publications Office of the European Union, Luxembourg. https://doi.org/10.2762/35894
Fish R, Winter M, Lobley M (2014) Sustainable intensification and ecosystem services: new directions in agricultural governance. Policy Sci 47:51–67
Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK (2005) Global consequences of land use. Science 309:570–574
Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O'Connell C, Ray DK, West PC, Balzer C, Bennett EM, Carpenter SR, Hill J, Monfreda C, Polasky S, Rockstrom J, Sheehan J, Siebert S, Tilman D, Zaks DPM (2011) Solutions for a cultivated planet. Nature 478:337–342
Francis C, Van Wart J, Johnson B (2014) How to regenerate rural community and ecoservices: reversing the tragedy of the commons. Agron J 106:95–99
Georgescu-Roegen N (1975) Energy and economic myths. South Econ J 41:347–381
Giampietro M (2018) Perception and representation of the resource nexus at the interface between society and the natural environment. Sustainability 10:2545
Giampietro M, Aspinall R, Ramos-Martin J, Bukkens S (2014) Resource accounting for sustainability assessment: the

nexus between energy, food, water and land use. Explorations in sustainability and governance series. Routledge, New York
Giampietro M, Bukkens S (2014) The multi-scale integrated assessment of societal and ecosystem metabolism. In: Giampietro M, Aspinall R, Ramos-Martin J, Bukkens S (eds) Resource accounting for sustainability assessment: the nexus between energy, food, water and land use. Routledge, London, pp 11–21
Giampietro M, Mayumi K, Ramos-Martin J (2009) Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): theoretical concepts and basic rationale. Energy 34:313–322
Gleick PH, Palaniappan M (2010) Peak water limits to freshwater withdrawal and use. Proc Natl Acad Sci USA 107:11155–11162
Global Land Project (2005) Science plan and implementation strategy. IGBP Secretariat, Stockholm
Hancock MH, Wilson JD (2002) Winter habitat associations of grey partridge (*Perdix perdix*) in Scotland. Asp Appl Biol 67:171–178
Hancock MH, Wilson JD (2003) Winter habitat associations of seed-eating passerines on Scottish farmland. Bird Study 50:116–130
Hein L, Obst C, Edens B, Remme RP (2015) Progress and challenges in the development of ecosystem accounting as a tool to analyse ecosystem capital. Curr Opin Environ Sustain 14:86–92
HM Revenue and Customs (2010) UK regional trade in goods statistics. http://www.uktradeinfo.com/index.cfm?task=td_regstats%hasFlashPlayer=true. Accessed 28 May 2011
Hoekstra AY, Mekonnen MM (2012) The water footprint of humanity. Proc Natl Acad Sci USA 109:3232–3237
Lambin EF, Geist H (eds) (2006) Land-use and land-cover change: local processes and global impacts. Springer, Berlin
Lambin EF, Geist HJ, Lepers E (2003) Dynamics of land-use and land-cover change in tropical regions. Annu Rev Environ Resour 28:205–241
Leach G (1976) Energy and food production. IPC Science and Technology Press Ltd, Guildford
Levin SA (2006) Learning to live in a global commons: socioeconomic challenges for a sustainable environment. Ecol Res 21:328–333
Lowe P, Woods A, Liddon A, Phillipson J (2009) Strategic land use for ecosystem services. In: Winter M, Lobley M (eds) What is land for?: The food, fuel and climate debate. Earthscan, London, pp 23–45
Mace GM, Bateman I, Albon S, Balmford A, Brown C, Church A, Haines-Young R, Pretty J, Turner K, Vira B, Winn J (2011) Conceptual framework and methodology. In: UK National Ecosystem Assessment (ed) The UK National Ecosystem Assessment technical report. UNEP-WCMC, Cambridge, pp 11–26
Marshall D (1946) Scottish agriculture during the War. Trans Highl Agric Soc Scotland, Fifth Series 58:1–77
Massimino D, Johnston A, Noble DG, Pearce-Higgins JW (2015) Multi-species spatially-explicit indicators reveal spatially structured trends in bird communities. Ecol Ind 58:277–285
Mayer AL, Buma B, Davis A, Gagne SA, Loudermilk EL, Scheller RM, Schmiegelow FKA, Wiersma YF, Franklin J (2016) How landscape ecology informs global land-change science and policy. Bioscience 66:458–469
Metzger MJ, Rounsevell MDA, Acosta-Michlik L, Leemans R, Schrotere D (2006) The vulnerability of ecosystem services to land use change. Agr Ecosyst Environ 114:69–85
Middleton TH (1923) Food production in war. Clarendon Press, Oxford
Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: synthesis. Island Press, Washington DC
Ministry of Agriculture, Fisheries and Food and Department of Agriculture and Fisheries for Scotland (1967) A century of agricultural statistics, Great Britain 1866-1966. Her Majesty's Stationery Office, London
Nesheim I, Reidsma P, Bezlepkina I, Verburg R, Abdeladhim MA, Bursztyn M, Chen L, Cisse Y, Feng S, Gicheru P, Koenig HJ, Novira N, Purushothaman S, Rodrigues-Filho S, Sghaier M (2014) Causal chains, policy trade offs and sustainability: analysing land (mis)use in seven countries in the South. Land Use Policy 37:60–70
Office for National Statistics (2017) Inflation and price indices. www.ons.gov.uk/economy/inflationandpriceindices. Accessed Nov 2017
Olmstead AL, Rhode PW (2001) Reshaping the landscape: the impact and diffusion of the tractor in American agriculture, 1910–1960. J Econ Hist 61:633–698
Perkins AJ, Maggs HE, Wilson JD (2008a) Winter bird use of seed-rich habitats in agri-environment schemes. Agr Ecosyst Environ 126:189–194
Perkins AJ, Maggs HE, Wilson JD, Watson A, Smout C (2008b) Targeted management intervention reduces rate of population decline of Corn Buntings Emberiza calandra in eastern Scotland. Bird Study 55:52–58
Perkins AJ, Whittingham MJ, Bradbury RB, Wilson JD, Morris AJ, Barnett PR (2000) Habitat characteristics affecting use of lowland agricultural grassland by birds in winter. Biol Conserv 95:279–294
Phalan B, Green R, Balmford A (2014) Closing yield gaps: perils and possibilities for biodiversity conservation. Philos Trans R Soc B. https://doi.org/10.1098/rstb.2012.0285
Pimentel D, Dazhong W, Giampietro M (1990) Technological changes in energy use in U.S. agricultural production. In: Gliesman SR (ed) Agroecology. Springer, New York, pp 305–321
Pimentel D, Pimentel M (1979) Food, energy and society. Edward Arnold, London
Pretty JN, Bret C, Gee D, Hine RE, Mason CF, Morison JIL, Raven H, Rayment MD, van der Bijf G (2000) An assessment of the total external costs of UK agriculture. Agric Ecosyst 65:113–136
Rivington M, Matthews KB, Buchan K, Miller DG, Bellocchi G, Russell G (2013) Climate change impacts and adaptation scope for agriculture indicated by agro-meteorological metrics. Agric Syst 114:15–31
Rural and Environment Research and Analysis Directorate (1939–present) Agricultural census (June). Series of annual census data. Scottish Government
Rural and Environment Research and Analysis Directorate (2009) Economic report on Scottish agriculture, 2009th edn. Scottish Government, Edinburgh

Rural and Environment Research and Analysis Directorate (2010) Economic report on Scottish agriculture, annual series, 1940 to present. Scottish Government, Edinburgh

Rural and Environment Science and Analytical Services (2016) Economic report on Scottish agriculture, 2016th edn. Scottish Government, Edinburgh

SAC (2008) Farming's retreat from the hills. SAC, Edinburgh

SASA (2009) Pesticide usage in Scotland. Arable crops 2008. Edinburgh

Scottish Government (2015) The future of Scottish farming: a discussion document. Scottish Government, Edinburgh

Scottish Government (2017) Results from the 2016 December agricultural survey

Sharpley A, Matlock M, Heathwaite L, Simpson T (2010) Managing agricultural catchments to sustain production and water quality. In: Ferrier RC, Jenkins A (eds) Handbook of catchment management. Wiley, Chichester, pp 107–132

Stamp LD (1958) The measurement of land resources. Geogr Rev 48:1–15

Symon JA (1959) Scottish farming: past and present. Oliver & Boyd, Edinburgh

The British Survey of Fertiliser Practice (2017) The British Survey of Fertiliser Practice—2016 Annual Report. Fertiliser use on farm crops for crop year 2016. Defra

Thomson S (2011) Response from the hills: business as usual or a turning point? An update of "retreat from the hills". SAC, Edinburgh

Tian Q, Brown DG, Zheng L, Qi S, Liu Y, Jiang L (2015) The role of cross-scale and environmental contexts in household-level land-use decisions. Ann Assoc Am Geogr 105:1240–1259

Tucker GM (1992) Effects of agricultural practices on field use by invertebrate-feeding birds in winter. J Appl Ecol 29:779–790

Turner BL, Lambin EF, Reenberg A (2007) The emergence of land change science for global environmental change and sustainability. Proc Natl Acad Sci USA 104:20666–20671

UK National Ecosystem Assessment (2011) The UK national ecosystem assessment: technical report. UNEP-WCMC, Cambridge

United Nations EC, Food and Agriculture Organisation of the United Nations, International Monetary Fund, Organisation for Economic Cooperation and Development, World Bank (2014) System of environmental economic accounting 2012: experimental ecosystem accounting. United Nations, New York

Vargas L, Willemen L, Hein L (2018) Linking planetary boundaries and ecosystem accounting, with an illustration for the Colombian Orinoco river basin. Reg Environ Change 18:1521–1534

Verburg PH, Eickhout B, van Meijl H (2008) A multi-scale, multi-model approach for analyzing the future dynamics of European land use. Ann Reg Sci 42:57–77

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of Earth's ecosystems. Science 277:494–499

Watson A, Perkins AJ, Maggs HE, Wilson JD (2009) Decline of Corn Buntings Emberiza calandra on east Scottish study areas in 1989-2007. Bird Study 56:213–220

Wright GG, Edwards AC, Morrice JG, Pugh K (1991) North east Scotland river catchment nitrate loading in relation to agricultural intensity. Chem Ecol 5:263–281