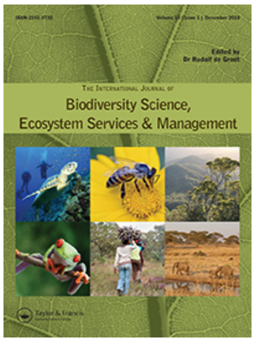

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RESEARCH

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Assessment of changes in ecosystem service delivery – a historical perspective on catchment landscapes

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ABSTRACT
Although the relationships between habitats and ecosystem services (ESs) have been acknowledged, investigating spatio-temporal change in these has received far less attention. This study assesses the influence of habitat changes on ES delivery across space and time, based on two time points some 60 years apart, 1946 and 2009. A 1946 aerial photo coverage of two catchments in Scotland was used to construct digital photo mosaics which were then visually interpreted and digitised to derive historic habitat maps. Using the Spatial Evidence for Natural Capital Evaluation (SENCE) mapping approach, the derived habitat maps were translated into ES maps. These were then compared with contemporary ES maps of the two catchments, using the same mapping methodology. Increases in provisioning ESs were associated with increases in intensively managed habitats, with reductions in supply capacity of other regulating and supporting ESs associated with loss of semi-natural habitats. ES delivery was affected not only by gross area changes in habitats over time, but also by changes in configuration and spatial distribution of constituent habitats, including fragmentation and connectivity. It is argued that understanding historic changes in ESs adds an important strand in providing baselines to inform options for current and future management of catchments.

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1. Introduction

River catchments have been subject to human modification for centuries, often tied to delivery of particular tangible benefits like food and water. However, more recently, demands have been increasing for catchments to deliver against broader ranges of benefits, including both tangible and less tangible ones. Managing catchments to deliver against these demands is challenging, because of needs to integrate understanding of both ecological systems (on the supply side) and social systems (on the demand side), and in turn has led to increased interest in the concept of ecosystem services (ESs). Frequently, ESs are defined as the benefits humanity derives from the natural environment (Millennium Ecosystem Assessment 2005), whether or not through intentional actions to maintain, enhance or alter natural environments. While human actions have increased flows of certain benefits, the ES concept is also drawn on to assess negative impacts and the scope to mitigate the latter, for instance through restoration ecology (Mulder et al. 2015). In Europe, highly modified river catchments are already a focus for the application of ESs thinking, in regard to, e.g., river network rehabilitation (Gilvear et al. 2013) and river biodiversity (Febria et al. 2015).

Multiple ESs may be supported within individual catchments. The Millennium Ecosystem Assessment (2005) grouped ESs into four key categories: provisioning ESs, covering the material products (e.g. water) obtained from ecosystems; regulating ESs, related to benefits achieved from regulation of ecosystem processes (e.g. flood regulation); cultural ESs, concerning the non-material benefits (e.g. recreation, aesthetic or spiritual) of ecosystems; and supporting ESs – the underlying ecological processes (e.g. soil formation) necessary for the production of all other ESs. Recognition of these different kinds of ESs has been feeding through into catchment management (Everard 2013), although importance attached to the coexistence of different services is slower to develop.

Managing multiple ESs together requires deepening understanding of the trade-offs and synergies which are possible across ESs within the same area. Trade-offs refer to inverse correspondence between different ESs where (in the simplest case of two ESs) the existence or increase of one service is linked to the absence or decrease of another (Rodríguez et al. 2006). Trade-offs frequently result from changes

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which increase the delivery of provisioning ESs from a landscape, but which also result in reductions in less tangible regulating and supporting ESs. Synergies are viewed as positive relations between ESs – presence/increase in one corresponds with a similar outcome for another – though synergies may also be negative.

Bennett et al. (2009) proposed a fuller typology of different situations where trade-offs and synergies occur, linking both exogenous drivers and interrelationships between ESs. This typology particularly helps illustrate the risk in managing ESs independently of one another, especially regarding trade-offs, whereby in the worst situation, both drivers and interrelationships are involved in adverse declines in certain ESs. However, by a similar token, knowledge of interrelationships in relation to drivers may also be a focus for management actions in order to enhance positive synergies between different ESs. Subsequently, related research has set about identifying and examining 'bundles' – common groupings of ESs and the contexts in which they typically occur – in order to elucidate those interrelationships (Raudsepp-Hearn et al. 2010).

Building up the required level of understanding ES interrelationships requires further research into ecosystem supply capacities spanning both space and time (Daily and Matson 2008; Haines-Young et al. 2012). 'Supply capacity' refers to the potential of an ecosystem to provide services, as distinct from actual levels of demand or supply. On the spatial dimension, proxy-based approaches are often taken to estimate ES supply capacity, which typically is difficult to assess directly (Seppelt et al. 2011). This includes map-based approaches whereby spatially explicit data on land use, land cover or habitats are the proxies on which supply estimates are based (Burkhard et al. 2012; Andrew et al. 2015; Science For Environment Policy 2015; Metzger et al. 2006; Glavan et al. 2013; Syrbe & Walz 2012; Maes et al. 2013; Vermaat et al. 2015). Maps of different ESs can be produced and compared for the same landscape; however, to date, this approach has been focussed almost entirely on contemporary landscapes and their delivery of different ESs, whereas methodologies for assessing ES changes over time are much more limited (Glavan et al. 2012; Haines-Young et al. 2012; Tomscha et al. 2016). In this study, it is argued that this is actually an important gap in understanding the ES potential of catchments. However, studies geared to tracking ESs and their inter-associations temporally can require long-term investment and commitment, which may be difficult to secure. For this reason, in studies which are addressing the temporal dimension, attention has been turning to the potential in historical records as data sources for investigating past conditions and changes between the past and present.

One kind of historical source attracting particular attention are photos from aerial surveys, available for many locations, flown for both state and commercial interests, and dating back several decades. Frequently, the photo scale and resolution of such surveys were selected to support the identification and interpretation of landscape features and attributes, including land use and habitat types. Consequently, it is feasible to consider the potential of historical aerial photos as inputs to mapping-based approaches to quantifying ES supply capacities at prior dates (Tomscha et al. 2016). Furthermore, the physical format of the aerial photos often supports copying and digitising, and the geographical extent and organisation of air surveys is another strength, in terms of offering comprehensive photo coverage over wide areas.

The present paper utilises historic aerial photos from surveys from the 1940s, in conjunction with recent habitat maps and ES mapping, to develop a spatio-temporal change assessment of multiple-priority ESs identified in two predominantly rural catchments in the Borders area in southern Scotland. The study catchments are human-dominated and dynamic, including agriculture and forestry as major land uses. These land uses are now better known for their negative impacts on biodiversity and ecosystems, yet such losses have also overshadowed positive effects that are being or may be delivered. The two study catchments have seen net increases in the extent of agriculture and forestry over the last 60 years, with evidence of a shift towards more intensive higher input–output systems as well. Intensification does, however, span different processes, and the relative importance of these different processes for understanding changes in ESs is not well understood (Tscharntk et al. 2005). These processes include local processes concerned with the management of specific plots (e.g. fertiliser and other chemical applications, tilling regimes, drainage) compared to processes operating on a wider landscape scale (e.g. land consolidation and enlargement of fields and reduction of their margins). The methodology developed for the present study focusses more on the latter, and enables supply capacities of different ESs to be assessed in relation to the spatial configuration of agriculture and forestry within the landscapes of the two study catchments. Subsequently, comparison of ES supply capacity levels at different dates affords a novel perspective on ES change in relation to expansion and intensification in major land uses in the catchments. It is argued that this has potential to inform further understanding of the interrelationships between locally important ESs.

2. Methods

2.1. Study area

The study catchments are located in the Borders area of southern Scotland, and both are sub-catchments of the approximately 5000 km^2 River Tweed Basin. The location and layout of the study sub-catchments are indicated in Figure 1, including a more detailed map of the Ale sub-catchment (170 km^2), which is the main one under study here. The sub-catchments were selected as a pair in part due to availability of data for this research, as detailed below. Field visits were conducted to assist with land use and habitat interpretation from the aerial photos, and it was easier to arrange these visits in the smaller of the two sub-catchments, the Eddleston, because of its smaller size (70 km^2) and also because other ongoing projects (Spray et al. 2016) made good links with the landowners there.

Both sub-catchments have much longer histories of improvement and modernisation primarily for farming, traced elsewhere to the late eighteenth and early nineteenth centuries (Harrison 2012). However, acceleration of anthropological pressures on ecosystems in the period since the Second World War is also well known (Newson 1997). The nature of the source materials available for this study, focused on visual evidence from the maps and aerial photos, supported comparison of changes in ES supply capacities linked to landscape-scale processes of intensification. Land management arrangements and practices are similar within the study sub-catchments; hence, similar results were anticipated at the outset of the study. This proved to be largely the case; hence, results reported in the paper are mainly for the Ale sub-catchment. Another reason to concentrate on the Ale sub-catchment is because of the prevalence of wetland habitats in the catchment, notably in the upper, west-lying section. Encroachment of commercial forestry plantation onto those habitats has been an issue, yet other stakeholder-based research also indicates positive attitudes towards maintaining and enhancing wetland presence within the sub-catchment (Tweed Medcalf and Williams 2010; Tweed Forum 2013).

2.2 Assessment methods

Central to the study are ES supply capacity maps created for two reference dates, 1946 and 2009. The former date is associated with the onset of major post-war pressures on ecosystems, whereas some 60 years later, the latter is at a time of increasing awareness of the multiple benefits provided by catchments. Figure 2 gives an overview of the workflow developed for the study, focussed on processes involved in creating historic ES supply capacity maps for 1946 and in conducting the change assessment between 1946 and 2009 (this date relates to the date of acquisition of aerial photos used to create contemporary ES maps) for each of the study catch-

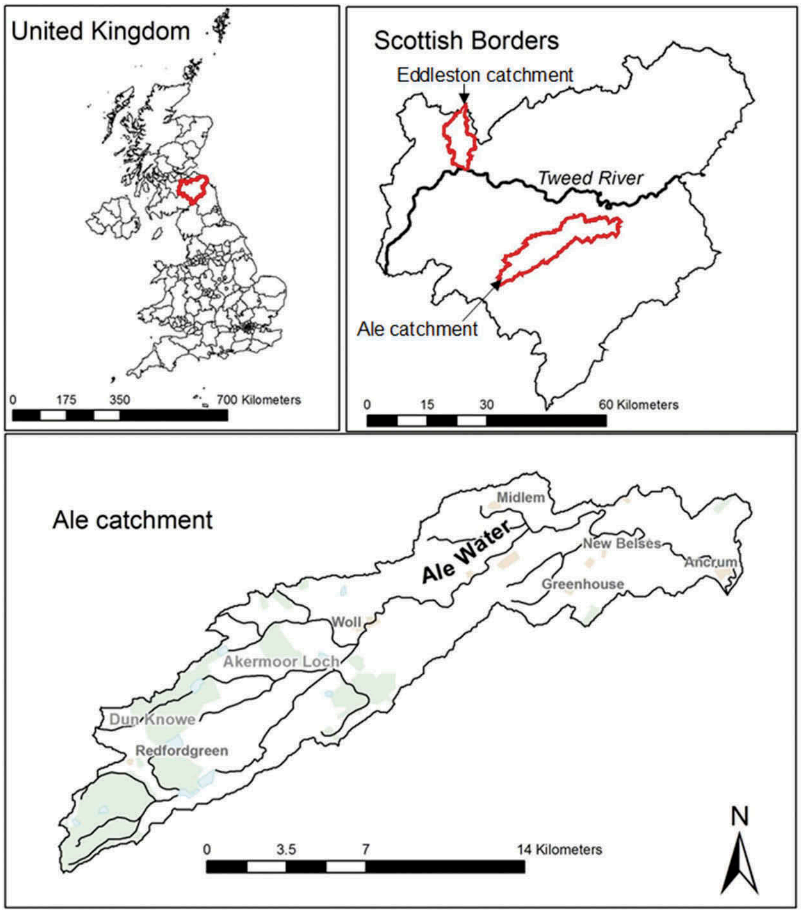

Figure 1. Ale and Eddleston catchments within the Tweed system in southern Scotland.

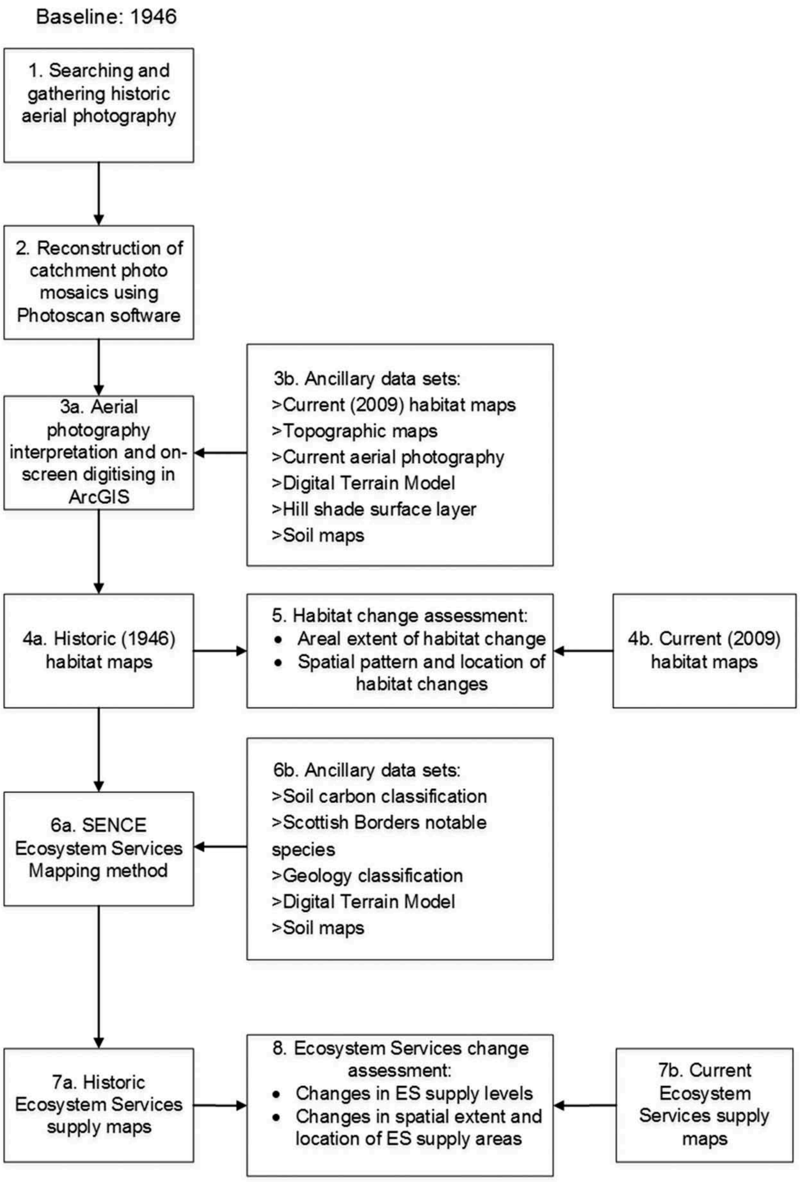

Figure 2. Procedure for historic habitat and ES mapping and change assessment.

ments. Key stages in this workflow are presented below.

It should be noted that ES supply capacity maps for 2009 had already been created as part of a Scottish Borders regional land-use strategy pilot project (Spray 2014), based on similar methods as those detailed here. In addition, the study built on other recent experience of using ES mapping tools (Vorstius and Spray 2015). For the change assessment, the focus was on 10 ESs, which had been identified as priority ESs for the study catchments as part of the aforementioned pilot project, and which could be mapped at both reference dates. These 10 ESs included in the change assessment are listed in Table 1. Excluded from this selection were cultural ESs, which could not be mapped for 1946 due to lack of required inputs.

Table 1. ESs selected for mapping in this study.

UK National Ecosystem Assessment (NEA) Ecosystem Service type	UK NEA Ecosystem Service Category	SENCE mapping tier level
Crop	Provisioning	1
Livestock		
Timber production		
Climate regulation:	Regulating	2
Soil carbon storage		
Vegetation carbon storage		
Detoxification and purification:		
Water quality		
Pollination		
Soil quality:		
Soil erosion control		
Water regulation:		
Water quantity		
Wild species diversity:	Supporting	2
Biodiverse habitats		

2.2.1. Aerial photo interpretation and habitat mapping

The historic baseline for this assessment commenced with repurposing aerial photos from a large survey of post-war Britain carried out by the Royal Air Force. The entire survey (Operation Revue) was done between 1944 and 1950 and was intended to assist in creating updated national mapping and planning purposes. For Scotland alone, the survey led to creation of over 280,000 aerial photos, now held within the National Collection of Aerial Photography by Historic Environment Scotland (HES). Both study catchments were included in sorties flown in 1946, yielding black and white aerial photos at a scale of 1:10,000. Digitally scanned versions of the complete set of aerial photos for both catchments were purchased for the study from HES. The aerial photos were first geo-registered and then used to create photo mosaics of the historic catchment landscapes using the Photoscan photogrammetric software package. The photo mosaics created by this process were in a format that could be handled, analysed and interpreted using geographic information systems (ArcGIS). However, due to the rather unsystematic manner in which the aerial photos had been taken, they do not always line up exactly with the boundaries of the catchments (which explains the overlaps and undershoots evident in the catchment maps presented in the 'Results' section below).

Subsequently, visual interpretation and on-screen digitising of the 1946 black and white photo mosaics were used to construct historic habitat maps (Figure 2, boxes 3a and 3b). Interpretation was done by the lead author after training and field visits to the Eddleston sub-catchment and was further supplemented by a review of literature available for both catchments. The aerial photo interpretation process was based on basic characteristics used to identify and classify features in aerial photos, as outlined by Morgan et al. (2010) and Lillesand et al. (2004). Such characteristics include feature shape, pattern, size, tone (greyscale variation), texture, shadow, site and association. Since aerial photo interpretation was done on black and white photo mosaics, differing shades of grey were mainly used to distinguish, identify and differentiate habitat classes. The relatively high spatial resolution of the photo mosaics made it feasible to distinguish features so that it was possible, for example, to interpret whether a woodland type was broadleaved, coniferous or mixed based on the shape of the tree crowns and height and shape of the shadow patterns. Where possible, evidence of local topographic variation and of management practice, e.g., visible plough lines, was similarly used.

A range of contemporary data layers was also made available to assist the historic aerial photo interpretation and habitat mapping, including the 2009 aerial photos and habitat mapping derived from those photos, plus topographic mapping, digital terrain model (DTM) surfaces and soils and land parcel boundary (hedgerows) data sets. These ancillary data sets showed landform, elevation, slope and surface relief and assisted in the differentiation of habitats based on their known location within the landscape. Maps of probable habitats in 1946 were produced in vector format based on an approach of backdating the existing 2009 habitat maps similar to the approach of Thomson et al. (2007) and Jauhiainen et al. (2007). This backdating approach involved overlaying the 2009 habitat maps onto the reconstructed 1946 photo mosaics, then editing the extents and classes of habitats shown in the 2009 maps using evidence garnered from the sources and processes just described. For example, areas of different habitats in 1946 were created by reclassifying 2009 polygons and/or by splitting them to align to habitat boundaries identified from the 1946 photo mosaics. This editing process resulted in a new habitat map with multiple attributes, including the interpreted 1946 habitat types. The habitat classes for both the 2009 and 1946 habitat maps were based on the Phase 1 habitat classification system. The Phase 1 habitat classification system is widely used in the UK as a standard approach for habitat classification (Joint Nature Conservation Committee 2010). The definition of habitat types in the Phase 1 habitat classification system is primarily based on dominant and characteristic vegetation species (Joint Nature Conservation Committee 2010). If vegetation is not the dominant component then topographic, soil, land use and other underlying characteristics are used.

2.2.2. Mapping ES supply capacities using the SENCE tool

The historic habitat maps in turn formed the main inputs for mapping historic supply capacities of the selected ESs. Several dedicated tools and methods supporting mapping of a number of different ESs are now available (Vorstius and Spray 2015). The Spatial Evidence for Natural Capital Evaluation (SENCE) tool had been used to create the 2009 supply-level maps for both catchments, and to afford a degree of consistency, it was also used to create the historic maps for this study. SENCE is a rule-based system with an associated set of look-up tables for translating multiple habitat types in terms of their ES supply capacity. The rule base for SENCE was developed by Environment Systems Ltd. through systematic analyses of research literature and expert opinion and is recognised and adopted as a reliable ES mapping approach by the main conservation agencies in the United Kingdom including the Joint Nature Conservation Committee (JNCC), Scottish Natural Heritage and Natural Resources Wales, as well as by the Scottish Borders Council (Medcalf et al. 2014).

The SENCE method is based on mapping ESs at two tiers, determined by the number and detail of available data sources in addition to the required habitat mapping (Figure 2, boxes 6a and 6b). For the first tier, habitat mapping is used as the only data source to map ESs, while for the second tier, other ancillary data on soil, topography, geology and elevation maps or primary data are integrated for greater detail, including local contextual factors influencing ES delivery. ES maps produced by the SENCE tool indicate the level of supply capacity for a given ES associated with each different habitat, ranked from no relevant capacity to very low, low, medium, high or very high capacity. Such ES mapping approaches which avoid the use of absolute values or numbers are covered in the report on Science For Environment Policy (2015). More detail on the SENCE ranking scale is provided in Appendices 1 and 2.

Using GIS, the SENCE look-up tables were joined to the historic 1946 habitat maps for both study catchments, to create new sets of habitat layers with allocated ES supply capacity rankings. These layers were then fed into a vector to raster conversion function to generate gridded maps of the supply capacity for each of the selected ESs. Conversion to a standard gridded spatial format facilitated integration with the ancillary data, and was done separately for every selected ES, given that each one had a different set of SENCE scores. Inclusion of a gridded base map formed from the collection of ancillary layers enabled the ES maps to be refined.

The ancillary layer collection had been produced previously as part of the Borders regional land-use pilot project and was convenient to use, on the assumption that the underlying factors of soil, geology and slope had the same importance in 1946 as in the contemporary period. The basemap formed from the ancillary collection could be tailored – e.g. for the ESs on water quantity regulation, it included ancillary data on soil and geology (superficial and bedrock) and from the DTM. In this way, tier 2 maps were produced by integrating initial ES maps with an appropriate basemap (precise combinations are indicated in Appendix 2). Tier 2 maps for the 1946 reference data were produced for all the selected ESs, except for those in the provisioning category, which instead were mapped at tier 1 only, i.e., based only on habitat distribution due to lack of availability of all relevant ancillary data.

2.2.3. *Assessing change in ES supply capacity over time*

Boxes 5 and 8 in Figure 2 show the main steps used to assess spatio-temporal differences between the two reference dates, for habitats and ES supply levels, respectively. ES maps for the two reference dates were used together to draw out the following three dimensions of change:

(a) generalised ES supply capacity levels in 1946 compared to those in 2009;

(b) change in areas ranked at the different ES supply capacity levels; and

(c) differences in the spatial extents of ES supply areas.

For dimension (a), a single overall supply capacity level for each ES was derived for both reference dates: these levels simply represent whichever supply capacity ranking (from no relevant supply capacity to very high) was most prevalent within the two catchments. This approach was used for all the selected ESs, save for those in the provisioning category. ESs in the provisioning group correspond with the major land uses of agriculture and forestry with the catchments, with each one being associated with one or just a few habitats. In this case, supply capacity levels and differences were assessed from the area occupied by each ES. For dimension (b), ES supply capacity map layers for 1946 and 2009 were compared directly, while for (c) frequency counts of grid squares allocated to each ES were also computed.

3. Results

3.1 *Habitat changes*

Comparison of the habitat maps for 1946 and 2009 showed increases in intensively managed habitats in both study catchments, notably in the areas of land under improved grassland and coniferous woodland plantations. In contrast, a decrease in area under arable land was observed. Decreases were also evident in areas under semi-natural habitat types, especially bogs, heathland, hedgerows and unimproved grassland areas (Figure 3). Linked to these changes were changes in spatial configuration of habitats, most notably the fragmentation of semi-natural habitats, which became interspersed among coniferous woodland plantations, especially in the uplands. Conversely, areas of intensively managed habitat types such as improved grassland did not show similar evidence of spatial fragmentation, having a higher proximity index and larger mean size in 2009 compared to 1946. Overall, the main conclusion drawn from such results is that habitats in the study catchments had become less diverse and more homogenous in 2009 compared to 1946. Further detail on these habitat changes is available in Ncube (2016). Figure 3 below shows examples of habitat changes in low-lying and upland areas of the Ale sub-catchment, as seen from 1946 and 2009 aerial photos.

3.2 *General changes in ES supply capacities between 1946 and 2009*

Figure 4 summarises the trajectories in general supply capacity for all 10 ESs considered by this study. For each individual ES, an indication of the general level in 1946 is shown on the left side of Figure 4; the level for 2009 is shown on the right side while the gradient of the connecting lines indicates an increase or

Removal of hedgerows and increase in field sizes in the low lying catchment areas

Upland bogs and heath replaced by coniferous woodland plantations

Figure 3. Examples of habitat changes observed from historic (1946) and current aerial photography (2009).

decrease. The diagrams are coarse but do provide some perspective on interrelationships between the different ESs within the two catchments, particularly broad-level trade-offs between the provisioning ESs associated with the major land uses and other ESs.

The differences shown in the diagrams mostly bear out initial expectations. For two provisioning ESs, timber and livestock, the supply capacity level increased, associated with increases in the area in forestry and grass in both sub-catchments. In contrast, for the crop production ESs, the general supply capacity level decreased, associated with a reduction in arable area, with parcels used for arable cropping in 1946 being switched to improved grassland in 2009.

For most of the other ESs, including biodiversity (supporting ecosystem service), and soil carbon storage, water quality regulation and pollination resource (regulating ESs), a general downshift in supply capacities is evident, corresponding with the reduction and fragmentation of semi-natural habitats evident from inspection of the habitat maps. Biodiversity and soil carbon storage ESs show a large downward shift in supply capacity, from very high in 1946 to a medium rank in 2009, while changes in the level of supply capacity appear to be smaller for other ESs. In contrast, for flood control and vegetation carbon, there was a general increase in supply capacity levels, associated with expansion in coniferous forest.

Notable differences in ES supply capacities between the two study catchments were in livestock production capacity, which shifted from high in 1946 to very high in 2009 in the Ale sub-catchment while in the Eddleston sub-catchment the shift was from medium to very high supply capacity. The supply capacity for crop production shifted slightly from very high in 1946 to high in 2009 in the Ale sub-catchment while the Eddleston sub-catchment showed a marked decrease from high to low supply capacity levels. The soil erosion risk control capacity level shifted upwards (‘medium’ to ‘high’) for the Ale catchment and it was in the opposite direction for the Eddleston sub-catchment.

3.3. *Changes in areas of high/very high supply capacity*

Visual comparison of maps for 1946 and 2009 was done to unmask changes in ES supply capacity levels in more depth. In particular, this showed landscape heterogeneity in supply capacity for most regulating and supporting ESs. A key concern is with persistence of areas having high or very high supply capacity rating for these ESs, despite general reductions over time.

The map results show that areas with high or very high supply capacity rating for these ESs were evident in 2009, but were much smaller and more dispersed than in 1946, associated with fragmented patches of

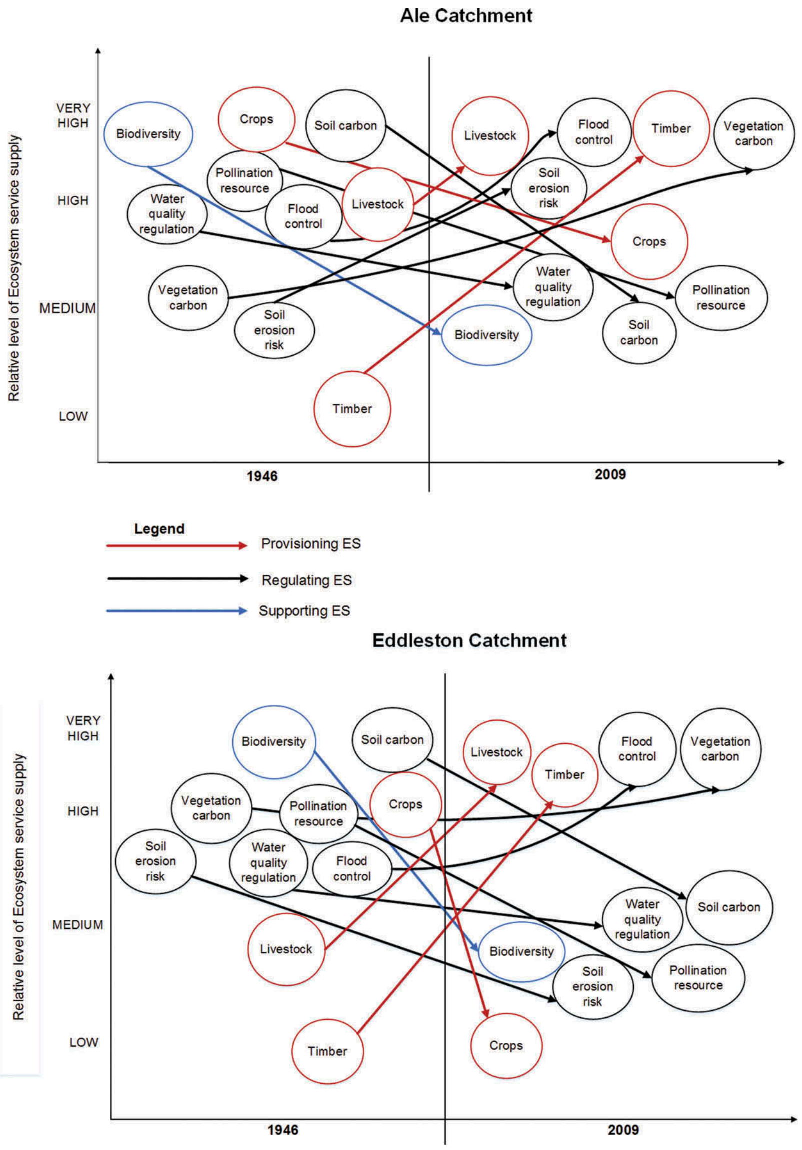

Figure 4. Changes in general relative rankings of the priority ESs.

semi-natural habitats in 2009. Figure 5 illustrates these changes as mapped differences for part of the upland section of the Ale sub-catchment (the extreme south-west area of the catchment). The top two maps illustrate habitat changes from upland bogs, heathland and acid grassland mosaics in 1946, which were mostly replaced by large stands of coniferous forestry by 2009. The other pairs of maps in the lower part of the figure show four of the priority ESs. For these ESs, there are obvious reductions from large areas with high or very high supply capacities in 1946 to lower supply capacity ratings in 2009. However, there are also a number of smaller high/very high capacity 'hotspots' in 2009. Comparisons across the 2009 maps indicate that there are some similarities in the location and extent of hotspots for the different ESs albeit spatial distributions are not identical. Potentially the similarities in these hotspots provide a basis on which to build further understanding and management of interrelationships in localised bundles of priority ES.

3.4 Changes in spatial location and extent of ES supply areas

Similar to subsection 3.2, the focus here is on a wider view on change across study catchments in their entirety. Due to space constraints, attention is confined to changes in just two ES types, timber provision and soil carbon storage, these being the ESs which saw some of the largest general changes between 1946 and 2009.

3.4.1 Timber provision

Changes in timber production capacity were assessed with reference to the changes in area under coniferous woodland between 1946 and 2009. As noted earlier, an increase in coniferous plantation was one of the major changes occurring between the two reference dates, the accompanying maps for the Ale sub-catchment illustrating both growth and spread (Figure 6).

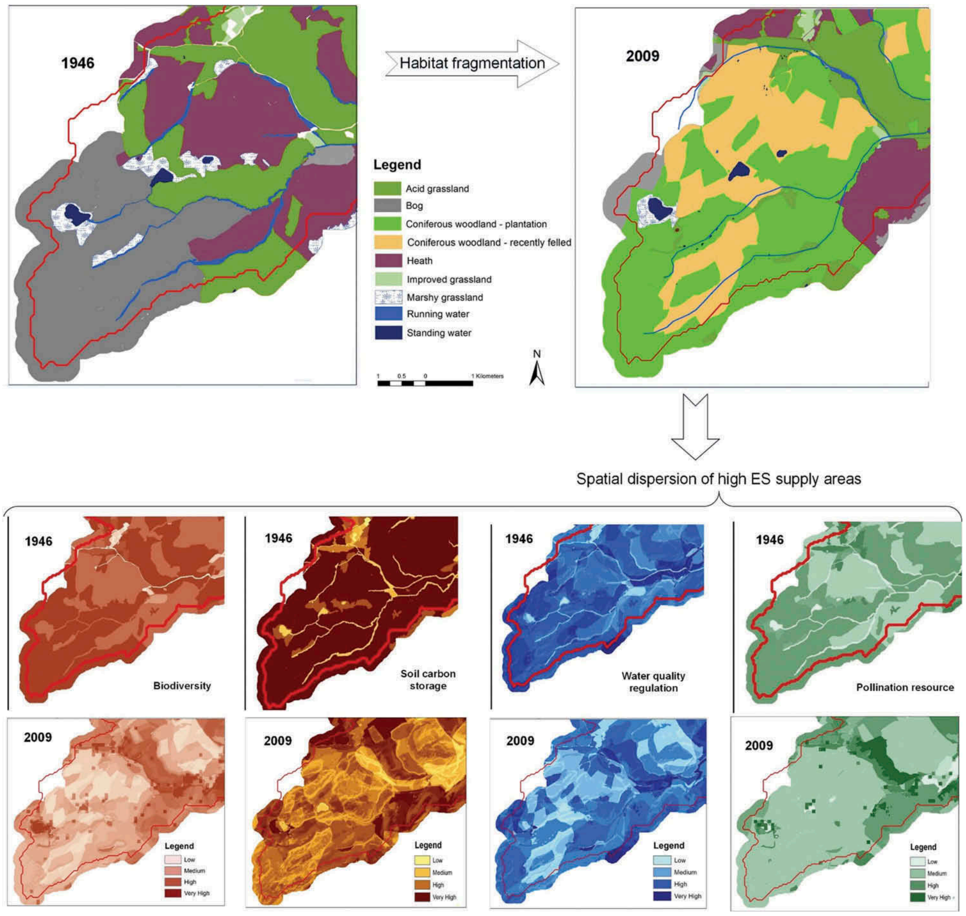

Figure 5. Impact of habitat fragmentation on spatial location of high ES supply areas.

In 1946, coniferous woodland was limited mainly to field parcel margins and boundaries in the lower section of the catchment, taking up less than 1% of the total catchment area. In contrast, in 2009, it occupied extensive tracts of land, in all three sections of the catchment, but especially in the uplands, totalling about 3,000 ha (21%) of the total catchment area.

3.4.2. Soil carbon storage

Figure 7 provides an illustration of change in supply capacity for soil carbon storage. The mapping shows the uneven spatial distribution in supply capacity levels across the catchment. Taking a whole catchment view highlights the concentration of areas having a very high supply capacity in 1946 in the upland section of the Ale catchment, associated with the areas classified in the 1946 habitat map as bog (wet bogs, blanket bogs), heath/acid grassland mosaics and unimproved acid grassland. In the eastern lower-lying section of the catchment dominated by agriculture, supply capacity levels were ranked low or medium, though even here some patches with high or very high supply capacities may be seen, associated mainly with other woodland plots and hedgerows.

In 2009, highest supply capacities for this ES remained concentrated in the upland catchment section, but at lower capacity ratings than in 1946: down from very high rating to high, medium or even low rating in some areas. In the lower section at the eastern end of the catchment, the 2009 map suggests homogenisation towards medium supply capacities with agricultural land-use conversion from arable cultivation to improved grassland, and with removal of hedgerows and tree-lined field boundaries.

The bar graph in Figure 7 shows more explicitly the shifts in supply capacity levels for soil carbon storage within the Ale catchment. The largest difference was in the percentage of the catchment having a medium supply capacity rating, from about 15% of the total catchment area in 1946 to over 45% in 2009. Much of this change was due to the downgrading of supply areas having a very high supply capacity, with the percentage of the catchment in this bracket dropping from about 40% in 1946 to about 17% in 2009. Conversely, a degree of upgrading is also evident, with the percentage of the catchment area with a low capacity level at over 20% in 1946 compared to about 12% in 2009. The percentage of the catchment having a high supply capacity remained about the same, only slightly greater in 2009 than in 1946.

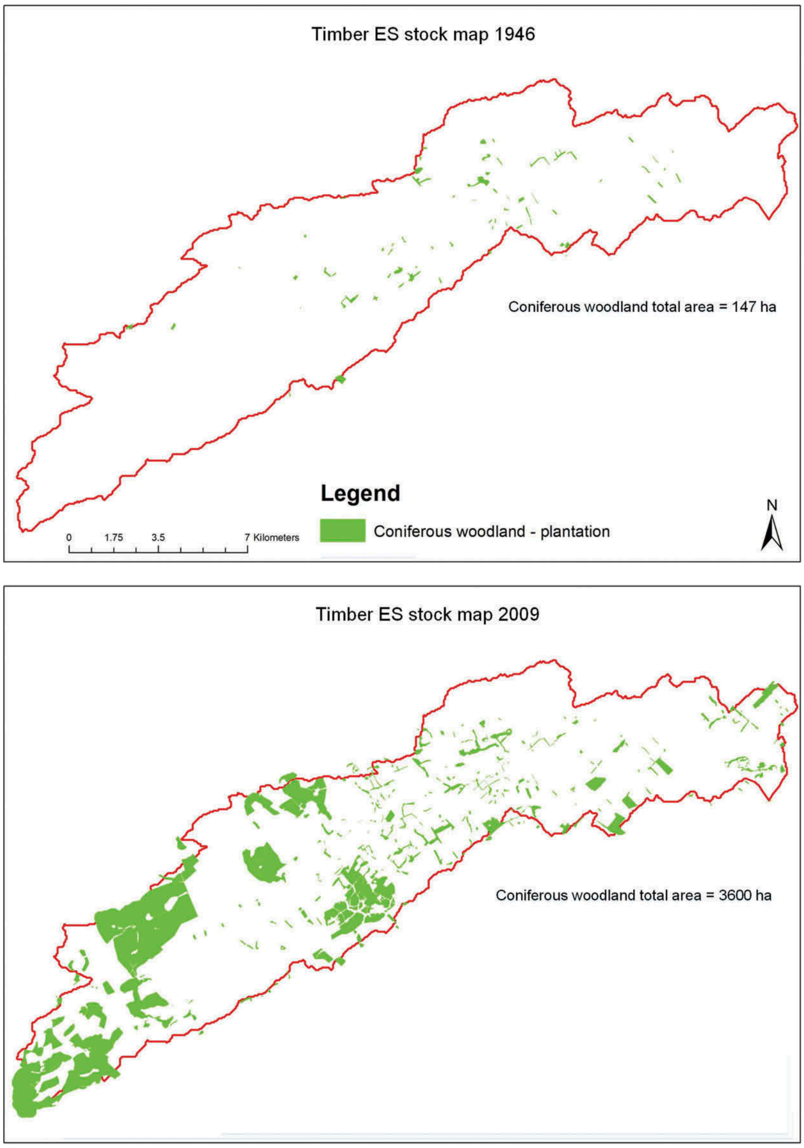

Figure 6. Timber provision areas in the Ale catchment.

4. Discussion

The present study has focussed on two predominantly rural catchments which are fairly typical in that they have already been highly modified, especially for the purposes of agricultural and timber production. These modifications have considerably longer history than the post-war period covered by the study; however, the increased rate of change and impacts on catchment ecosystems in the decades since the Second World War provide particular cause for concern. The main drivers of change in this period have been detailed elsewhere, e.g., Miller et al. (2009) and UKNational Ecosystem Assessment (2011). In particular, the UK agriculture and afforestation policy and legislation introduced in the late 1940s are well known as key influencing factors (Bowers 1985). Alongside economic and technological changes (Robinson and Sutherland 2002), these political factors influenced changes in land management and practices, including conversion of land between different agricultural uses and land deemed as being of low agricultural value into woodland or forestry. By 2009, productivist demands on catchments associated with these drivers had contributed to a situation whereby intensively managed habitats and provisioning ESs associated with these major land uses dominated the study catchments.

Addressing this management challenge requires deepening understanding of how ESs within catchments interact with one another and how they each respond to different drivers, so that delivery of multiple ES benefits may be attained or enhanced. One pressing issue in this regard is for understanding that informs management of trade-offs linked to provisioning ESs. These trade-offs have been closely associated with intensive systems of agricultural and forestry land uses, yet it is crucial to recognise that maintenance of other ES types, particularly regulating ESs, is integral to provisioning ES benefit flows that those systems are intended to deliver – a point emphasised by other

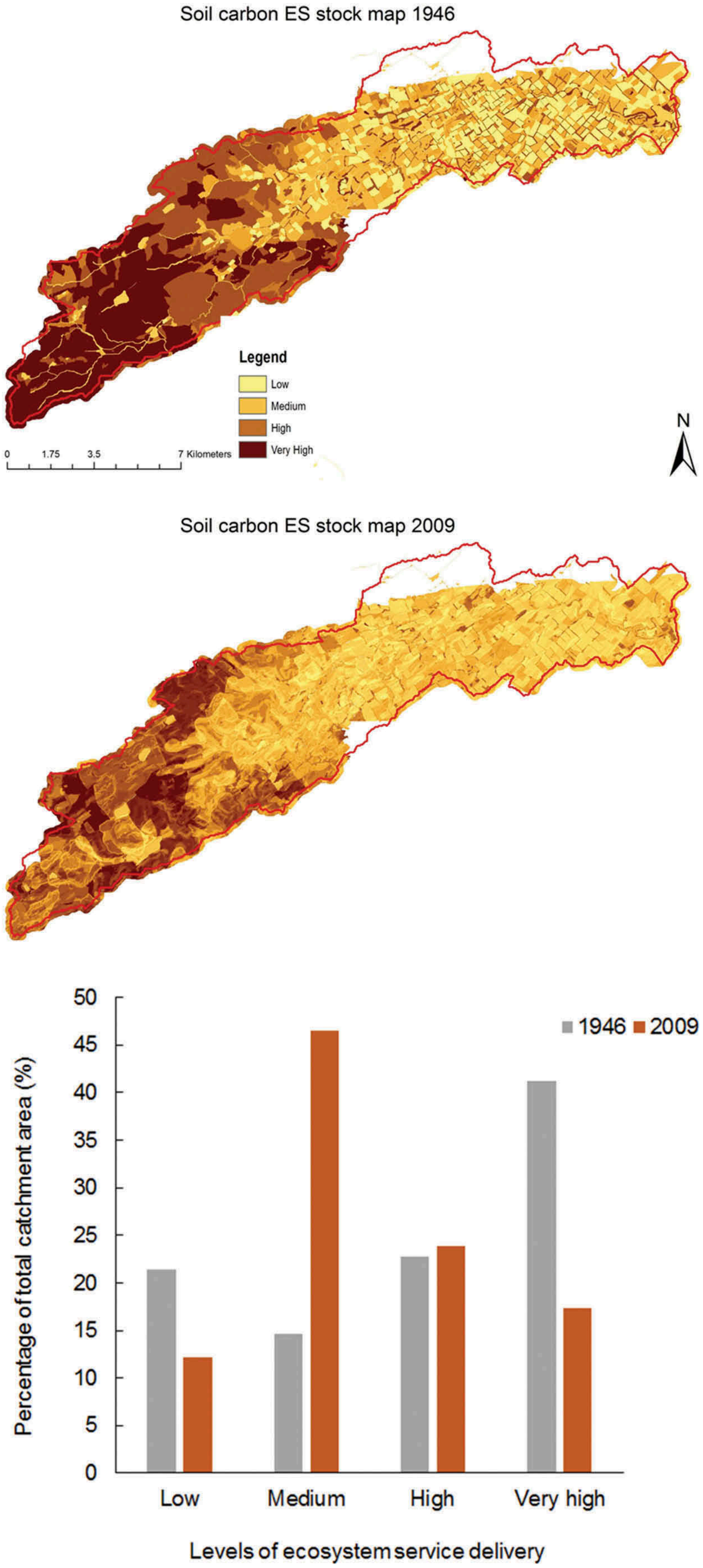

Figure 7. Soil carbon storage stock map for the Ale catchment.

commentators (Raudsepp-Hearne et al. 2010; Haines-Young et al. 2012; Maes et al. 2012; Jopke et al. 2015; Science For Environment Policy 2015; and Queiroz et al. 2015).

Furthermore, there is also evidence that lower-intensity (often more traditional) systems can also contribute positively to a range of ESs and thus towards socio-ecological resilience. This in turn raises questions regarding how currently intensive systems may be altered in order to achieve those synergies whilst maintaining provisioning ESs at satisfactory levels (Firbank et al. 2013). Interactions, synergies and trade-offs between different ESs can be assessed in different ways, such as through other work to identify and characterise commonly found bundles of services (Bennett et al. 2009; Raudsepp-Hearne et al. 2010). In the present study, the selection of ESs was predetermined from previous research conducted with local stakeholders in the two study catchments. Interactions between the selected 10 ESs (though not all possible combinations of them) have been explored in this paper.

Understanding service interrelationships may be built up in different ways, with one avenue involving a mapping approach, focussing on assessing spatial patterns across landscapes. However, mapping-based assessments have focussed more on patterns at single points in time rather than on patterns over time as well as in space. As mapping of ESs increases, it is also to be expected that spatio-temporal assessment will become more prevalent.

Nonetheless, spatio-temporal studies covering already historic periods will remain less common given the lack of availability of ES maps for dates before present – and this despite warnings against ignoring history, as argued in more detail elsewhere (Tomscha et al. 2016). This study adds to demonstrations of the utility of historical aerial photos within mapping approaches as a means for filling this gap. In other studies, aerial photos have been used for direct estimation of levels of certain ES. In this study, historical aerial photos for 1946 were used in conjunction with current habitat maps and other ancillary data to derive classified historic habitat maps, and then historic ES maps, using an established mapping tool (SENCE). The ES maps used alongside with those for 2009 afforded new insight on multiple aspects of change up to the present time: differences in the areas occupied by habitats and provisioning ESs; differences in supply capacity levels of supporting and regulating ESs; and differences in the spatial variability exhibited by individual ESs and in ES co-patterning across the study catchment.

The habitat changes identified through this study are similar to those reported elsewhere (Mackey et al. 1994; Cooper et al. 2003; Hooftman and Bullock 2012). By 2009, the area of the catchments from which provisioning ESs of livestock and timber production were derived was considerably larger than 60 years earlier, though the area in crop production had decreased, notably due to transfer of land from cropping into grassland for livestock purposes. Overall, the area dedicated to provisioning ESs had increased, and the results also extend empirical evidence of the trade-offs associated with these increases, indicating general decreases in supply capacities of most other regulating ESs, and even larger general decreases in the biodiversity supply capacity (a supporting ES).

These trade-offs included one-to-many configurations, i.e., whereby a single type of habitat change, such as from semi-natural upland bog habitat into coniferous woodland, was associated with trade-offs with multiple ES changes (e.g. in soil carbon storage, biodiversity and pollination). This reflects the multi-functional role of semi-natural habitats in ES delivery, as reported in other studies (Burkhard et al. 2012; Vrebos et al. 2015; Crouzat et al. 2015; and Lamy et al. 2016). In contrast, intensively managed habitat types such as coniferous wood or arable land are more homogenous, have less habitat diversity and hence have lower capacities to supply multiple ESs (Burkhard et al. 2012).

However, there are also indications of synergies, in the form of general increases evident in supply capacity levels for vegetation carbon storage and flood control linked to timber production expansion in the catchments. Similar synergies have been observed in other studies, e.g., Jiang et al. (2013). However, the impacts of timber management activities also have to be factored in. For example, tree planting and timber harvesting may contribute to increased run-off and soil erosion risk (Bunce et al. 2014). Wider impacts on catchment hydrology (Bunce et al. 2014) and on species population dynamics (Fahrig 2007) have also been noted, as they have effects on biodiversity ES, which itself impacts on the delivery of multiple other ESs (Mace et al. 2012).

A strength of the mapping approach adopted for this study is that it enabled a direct and visual means to assess spatial variability in ESs within the catchments. For example, visualising maps of soil carbon storage illustrated heterogeneity in supply capacity levels across landscapes linked to habitat and biophysical characteristics and gradients. The increases in major land uses and reduction in semi-natural habitats by 2009 had not removed this heterogeneity altogether, although reduction and smoothing out of spatial variability in capacity levels were apparent compared to situation in 1946. More detailed map comparison for the western upland section of the Ale catchment indicated that areas with high capacity levels for the regulating and supporting ESs still existed in 2009 but were much smaller and spatially more dispersed than in 1946, linked to fragmentation of semi-natural habitats. The persistence of these ‘hotspots’ of high or very high supply capacity for a range of different ESs may be construed as a positive finding, although there are questions regarding the minimum size of such areas and their arrangement within other habitats in order that they can make an effective contribution to delivery of desired ESs as well as to diversity and multifunctionality.

The study adds to the demonstrations of the utility in assessing historical catchment conditions to inform current management questions and choices (see also Glavan et al. 2012, 2013; Tomscha et al. 2016). Maps of historic and present-day habitats and ESs themselves provide a means to engage and inform land managers and other stakeholders, and furthermore, the visualisations they provide may contribute to instilling more holistic (i.e., whole catchment) management approaches. At this point, it is also important to observe that while the post-war productivist paradigm is being left behind, more recent policy shifts since the 1980s to encourage more sustainable agricultural and forestry systems have not stemmed ecological or biodiversity losses associated with intensive systems in some regions (Stoate et al. 2009), and that it is precisely because of their failure to adopt landscape-wide perspectives that current EU agri-environment schemes have been repeatedly criticised as being of limited effectiveness (Tscharntk et al. 2005; McCracken et al. 2012). Moreover, as well as potentially supporting better targeting and more holistic management, the kind of maps produced and used within this study provide further opportunities for learning and knowledge insights through comparing trajectories in spatio-temporal change for different landscapes. The comparison of the two catchments in this study hints at such possibilities.

Current proxy-based mapping methods and tools, including the method used in this study, are not without their own criticisms and limitations, including the use of relative rankings of ES supply capacity, and the assumed linear relationship between habitat changes (quality and quantity) and ES delivery (discussed further by Koch et al. 2009), while Eigenbrod et al. (2010) go as far as to question the suitability of proxy-based approaches for identifying hotspots or priority areas for multiple ES delivery.

Given these assumptions and limits, there are risks of ‘pushing’ the maps to too high degree of scrutiny. The fact that maps cannot provide definitive evidence of interrelationships is one reason for the generalised nature of the findings reported in this paper. In addition, means for assessing map accuracy and validation of maps remain insufficiently addressed in many current ES mapping practices (Schulp et al. 2014; Willemen et al. 2015), although different modes of stakeholder consultation are now being explored to address such shortcomings (Vrebos et al. 2015). In this study, the 2009 ES maps produced for the Scottish Borders regional land-use pilot project were validated by the local stakeholders and also led to certain refinements of the ES maps. Of course, it was not feasible to conduct a stakeholder validation exercise for the ES maps for 1946.

Finally, historically focussed research is also not without its challenges, including practical issues connected with repurposing historical sources and conceptual questions of how to interpret supply capacities within past contexts and within complex and dynamic socio-ecological systems (Tomscha et al. 2016). In this study, assessment of change over time was limited to two reference dates defining the start and end of a study period. Clearly this approach captures only net change between two time points, rather than all the changes occurring between them. In addition, the ancillary spatial data on soil, topography and geology used in this study are for the present-day period rather than for 1946. Using these data therefore involves assuming that these characteristics concerned are broadly unchanged between the two study dates.

5. Conclusion

This study demonstrates benefits of extending existing ES mapping methods to assess spatio-temporal change in the delivery and supply capacity of ESs within the context of two typical rural British river catchments. The focus is on assessing historic change in the six post-war decades, and it is argued that the study approach can yield knowledge of service interrelationships useful for present-day catchment management. The study shows the possibilities of repurposing historic aerial photos to derive both historic habitat maps and historic maps for a range of priority ESs, including provisioning, regulating and supporting ESs. Comparison of historic maps for 1946 and present-day maps for 2009 affords a perspective on spatio-temporal change in various interrelationships, including between-habitat changes and changes in different ESs. This includes visualising and quantifying changes in the locations in which the selected ESs are delivered, changes in supply capacity, and changes in heterogeneity, i.e., spatial variability in supply capacity levels across the study catchments. Notable results are the expansion of areas in intensively managed habitat types between the two study dates, especially in intensively managed agricultural grassland and coniferous forest plantation, with associated increases in extents of associated provisioning-type ESs but traded-off against reductions in supply capacity levels of most of the regulating and supporting ESs. Areas of high supply capacity of the latter also became more fragmented and dispersed, into ‘hotspots’, but did not disappear altogether from the study catchments, in turn raising questions about the level of trade-off possible between habitat changes and delivery of multiple ESs at desirable levels. ES delivery is affected not only by changes in gross area of constituent habitats, but also by spatial changes in the configuration and distribution of these habitats.

It is also concluded that map-based approaches for assessing historic spatio-temporal changes in interrelations may help inform management of catchments today. Mapping different ESs across habitats may help encourage holistic landscape-wide management approaches. In addition, the associations of habitat change with ES delivery, and identification of areas continuing to have high supply capacity levels for regulating and supporting ESs, may inform land use and landscape planning to deliver on ES targets set for entire catchments.

Map copyright

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No potential conflict of interest was reported by the authors.

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Appendix

Appendix 1: SENCE habitat and ES ranking scale

Habitat	Water quantity	Water quality	Vegetation Carbon	Soil Carbon	Pollination	Biodiversity	Land erosion risk control
Acid grassland – semi-improved	100	150	50	100	150	200	100
Acid grassland – unimproved	100	150	50	150	150	250	200
Blanket bog	200	200	200	250	100	250	150
Bracken – scattered	100	150	150	50	50	150	150
Bracken – continuous	100	150	200	100	50	100	200
Broadleaved parkland/scattered trees	250	150	250	100	100	200	150
Broadleaved woodland – plantation	250	150	250	200	100	200	250
Broadleaved – recently planted	200	100	150	50	0	50	100
Broadleaved woodland – semi-natural	250	250	250	200	100	250	150
Built land	0	0	0	0	0	0	50
Coniferous woodland – plantation	250	150	250	100	0	100	150
Coniferous woodland – recently planted	200	100	150	50	0	50	50
Improved grassland – amenity	50	50	50	150	50	50	200
Cultivated/disturbed land – arable	0	0	0	50	250	200	50
Dry dwarf shrub heath	150	150	200	200	250	200	150
Dry heath/acid grassland	150	150	150	250	100	150	150
Dry modified bog	50	0	100	50	0	0	100
Fen – valley mire	200	150	150	50	0	0	50
Flush and spring – acid/neutral flush	200	150	50	250	100	200	50
Gardens	50	50	50	200	100	200	100
Hedgerow	150	200	200	50	100	100	200
Improved grassland	50	0	50	150	150	50	150
Marsh/marshy grassland	200	150	100	50	50	100	150
Mixed woodland – plantation	250	150	250	150	100	250	200
Neutral grassland – semi-improved	100	150	50	50	50	50	50
Neutral grassland – unimproved	100	150	50	200	50	150	150
Other tall herb and fern	100	50	50	100	0	50	150
Poor semi-improved grassland	100	150	50	100	50	150	100
Quarry	0	0	0	0	0	0	50
Refuse tip	0	0	0	0	50	50	50
Running water	0	0	0	0	50	50	50
Scrub – dense/continuous	200	200	150	50	50	150	250
Scrub – scattered	150	200	100	150	250	100	150
Standing water	0	0	0	0	50	150	0
Wet bog	200	200	150	250	150	200	50
Wet dwarf shrub heath	150	200	150	200	200	250	150
Wet heath/acid grassland	150	200	150	150	150	250	150
Wet modified bog	100	100	150	200	100	250	100

ES supply capacity scores:
0 = No relevant supply capacity to supply the selected ES
50 = Very low supply capacity to supply the selected ES
100 = Low supply capacity to supply the selected ES
150 = Medium supply capacity to supply the selected ES
200 = High supply capacity to supply the selected ES
250 = Very high supply capacity to supply the selected ES

Appendix 2: Data sets and attributes used to map selected ESs

Agricultural crops			NEA service type: Provisioning
This map covers areas used for crop production, the intensive production of arable crops and in some cases the small-scale vegetable production in the backyard gardens/allotments.			
Significant effects	Data used	Example attributes	Indicative scoring
Likelihood of land cover to support food production	Phase 1 (1946) habitat layer	Arable/Not arable	Very high/No relevant supply capacity
Agricultural livestock			NEA service type: Provisioning
This map covers areas which support livestock including arable crops grown for animal feed, intensively grazed areas and extensive permanent grazing regimes. It is assumed that improved and semi-improved grasslands provide this ES.			
Significant effects	Data used	Example attributes	Indicative scoring
Presence of suitable grazing environments	Phase 1 habitat layer (1946)	Improved grassland/Semi-improved grassland/other habitat mosaics	Medium/Very low
Timber resource			NEA Service type: Provisioning
The map covers areas within the lands that have woodland plantations and semi-natural woodland occurrences. Since plantation woodland has management and growth stages, the type of woodland and planting regime affect how long until the timber resource is ready. Late-stage forestry, mature coniferous plantations were given the highest score as they are most likely to provide the maximum timber resource. Recently planted and felled woodland was given a lower score as it will take years before timber is available from such sites. Broadleaved and mixed woodlands were given a very low score as few trees are felled at a time for specific site management purposes.			
Significant effects	Data used	Example attributes	Indicative scoring
Provision of coniferous plantation	Phase 1 habitat layer (1946)	Plantations Other woodlands	Very high/Very low
Soil carbon storage			NEA service type: Regulating
Soil carbon storage results from interactions of different ecological processes. The amount of organic matter present within the soil profile is an important component which contributes to this ES. Soil organic matter is a heterogeneous mixture of organic compounds that are highly enriched in carbon, ranging in decomposition from leaf litter, to highly decomposed material (humus). Soil organic carbon levels of different soil types are directly related to the amount of organic matter contained in soil from growth and death of plant roots and foliage, as well as indirectly from the transfer of carbon-enriched compounds from roots to soil microbes. Inorganic carbon is not readily released into the atmosphere or water from the soil so it has not been considered in this analysis.			
Significant effects	Data used	Example attributes	Indicative scoring
Presence of organic carbon in the soil	Soils National Soil Survey of Scotland 1:250,000 (including SNH soil carbon classification)	Organic soils Mineral soils	Very high/High Medium/Low/Very Low
Topography suitable for soil carbon accruement	Elevation Slopes derived from DTM	Shallow slope Steep slopes	Very high/High Very low/low
Vegetation cycle accrues/releases soil carbon	Phase 1 habitat layer (1946)	Wetlands and woodlands/Heathland/Semi-natural grassland/Improved grassland/High-intensity agriculture	Very high High Medium Low Very low No relevant supply capacity
Vegetation carbon storage			NEA service type: Regulating
Atmospheric carbon is sequestrated by, and stored in, vegetation. Habitat type is a key determinant of vegetation carbon storage, the more biomass that is present in the vegetation layer the more carbon is stored, with mature woodland at one end of the spectrum and grasslands at the other end. It has been estimated that woodlands and forest vegetation hold up to 80% of the UK total vegetation carbon with those habitats managed for arable and horticultural crops storing the least carbon in their vegetation.			
Significant effects	Data used	Example attributes	Indicative scoring
Biomass presence	Habitats Phase 1 habitat layer (1946)	Woody species Other scrub vegetation Other short vegetation	Very high/High Medium Low/Very Low
Water quality regulation			NEA service type: Regulating
Water quality is influenced by both natural processes and human activities. Soil temporarily stores water that falls as rain and subsequently releases it to rivers and streams, or adds it to the overall groundwater resource. Some soil types effectively filter water as it percolates through it, whilst others add to the suspended particulate matter and mineral content of the water. Steep slopes shed water more rapidly than shallow slopes. Habitat type, through its link to vegetation structure and type and soil type, has an important influence on water quality. Some vegetation species play a role in water purification.			
Significant effects	Data used	Example attributes	Indicative scoring
Presence of vegetation	Phase 1 habitat layer	Woodland Hedge Heathland Bog Arable	Very High/High Medium Medium Low/Very low Low
Filtration effect of the soils	Soils National Soil Inventory Scotland 1:250,000	Brown earths Peaty soils	Very High/High/Medium Low
Slope is linked to flow rate	Elevation Slopes derived from DTM	Steep slopes	Very low/Negative
Land erosion control			NEA service type: Regulating

(*Continued*)

(Continued).

The susceptibility of land to erosion can be seen as a composite of how easily the substrate can be eroded, and any mitigating effects of the surface vegetation. The higher the risk of erosion the more vulnerable the soil profile and higher the risk of sediment transport to watercourses. By identifying the risk, areas vulnerable to land-use change can be targeted for mitigation work or run-off control measures.			
Significant effects	Data used	Example attributes	Indicative scoring
Soil and slope characteristics	JHI Inherent risk of erosion by overland flow	Soil texture, run-off and slope characteristics = prone to erosion Soil texture, run-off and slope characteristics = less prone to erosion	Low/Very low Very high/High
Vegetation preventing erosion	Phase 1 habitat layer (1946)	Sparsely vegetated areas Arable land – regularly bare Dense vegetation (e.g. woodland, heaths, bogs)	Medium Low/Very low Very high/High
Pollination resource			NEA service type: Regulating Supporting
A biotic pollinator is any living organism that moves pollen from the male anthers of a flower to the female stigma of a flower, enabling fertilisation. The pollination resource can be seen as the amount of pollen present in an area. Areas poor in pollen-producing species are unable to produce enough pollen to support pollinator species. Pollinators are essential for the maintenance of many habitat types and production of insect-pollinated crops. Pollination as a service is not often mapped due the relatively small scale of the process. Most common known proxy methods to map pollination involve the use of land cover and land use, pollinator habitat and crop yields.			
Significant effects	Data used	Example attributes	Indicative scoring
Species which affect pollination	Species Borders notable species	Bee species Butterflies & moths Dragonflies (associated with pollinator predation around water)	Very high/High Medium No relevant supply capacity
Species which produce pollen	Species Borders notable species	Flowering plants	Very high/High
Indicative pollen presence	Phase 1 habitat layer (1946)	Habitat often contains a high proportion of pollen-rich species (e.g. heath, scrub) Habitat often contains some pollen-rich species (e.g. semi-natural grassland) Habitat contains few pollen-rich species (e.g. woodland, improved grassland) *Insect-pollinated flowering crop (e.g. oil seed rape, legumes, potatoes)* *Non-insect-pollinated crop (e.g. silage, oats, wheat)*	Medium/high Medium Low Medium Very low
Water quantity			NEA service type Regulating
Water quantity regulation is a key ES as excess water in a natural system can cause flooding events. The regulation of water is complex and is affected by factors such as climate (rainfall), but also less obvious ones such as topography, soil, vegetation and land-cover type (such as concrete and tarmac). Soil temporarily stores rain water as it percolates through the system towards rivers and streams, or into the groundwater resource. The ability of soil to perform this function depends on its texture, depth and organic matter content, as well as the overall context of the soil in the landscape. Habitat type, through its link to vegetation type and soil type, has an important influence on water quantity. This is greatly influenced by the structure of the vegetation present and its effect on infiltration. Steep slopes shed water more rapidly than shallow slopes. Steep slopes are also more likely to be in the upper reaches of catchments and are characterised by small streams with rocky banks, which in times of heavy rainfall can quickly rise.			
Significant effects	Data used	Example attributes	Indicative scoring
Vegetation effect on interception	Phase 1 habitat layer (1946)	Dense vegetation (e.g., woodland) Variable-density vegetation (e.g. heath, bog) Low-density vegetation and vegetation often removed (e.g. arable)	Very high/High Medium Low/Very low
Infiltration and drainage characteristics of the ground	Soil/geology National Soil Inventory Scotland 1:250,000 with HOST classification BGS Superficial 1:50,000 BGS Bedrock 1:50,000	Free drainage Poor drainage Permeable substrate Impermeable substrate	Very high/High Low/Very low Very high/High Low/Very low
Drainage	Drainage and topography DTM	Gentle slopes/Steep slopes	Very high/High/Low/Very low
Biodiversity and nature conservation			NEA service type: Regulating and maintenance Provisioning Supporting Cultural

(*Continued*)

(Continued).

Biodiversity is an important supporting ES that underpins a majority of ESs. Biodiversity describes the range and diversity of species existing and includes genetic diversity within species and between different taxa in any area.

Climax communities of semi-natural habitats that have been present for a long period of time tend to have the highest biodiversity, as over time they can develop specialised niches. The structure of the vegetation both above and below ground has a profound effect on biodiversity. The more complex the structures and the more varied the niches or locations for biodiversity development the greater the diversity of species found in an ecosystem.

The value of a parcel of land for biodiversity and nature conservation can be assessed by considering:

Naturalness – those habitats which have received little modification by humans.

Diversity – The higher the plant community species richness, the higher the diversity within the habitat. This is difficult to accurately compare as some plant communities are intrinsically more species-rich than others. Detailed habitat classifications such as Annex I or NVC, which take into account the presence of species and communities, can be added to the broader habitat classifications to model species diversity.

Connectivity – Habitats which are well connected are more likely to support a greater number of organisms that inhabit that particular ecological niche. Fragmented patches (depending on size) can only support smaller populations.

All vegetation types have been scored in this biodiversity layer and then any management and connectivity have been added as modifiers to infer more likelihood of good quality habitat.

Significant effects	Data used	Example attributes	Indicative scoring
Naturalness	Habitats Phase 1 habitat layer (1946)	Semi-natural habitats (e.g. heath, bog, woodland) Other habitat (e.g. scrub, parkland, bracken) Intensively managed land (e.g. improved grassland, arable, urban)	Very high/High Medium Low/Very low
Diversity	Species Borders Notable Species	Internationally important Nationally important Locally important	Very high/High Medium Low/Very low
	Habitats Phase 1 habitat layer (1946)	Other habitat (e.g. scrub, parkland, bracken) Intensively managed land (e.g. improved grassland, arable, urban)	Medium Low/Very low
Location within the landscape	Phase 1 habitat layer (1946)	Well-connected habitat Poorly connected habitat	Very high/High Low/Very low

BGS - British Geological Survey
DTM - Digital Terrain Model
JHI - James Hutton Institute
NEA - National Ecosystem Assessment
SNH - Scottish Natural Heritage