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Quantifying gross vs. net agricultural land use change in Great Britain using the Integrated Administration and Control System

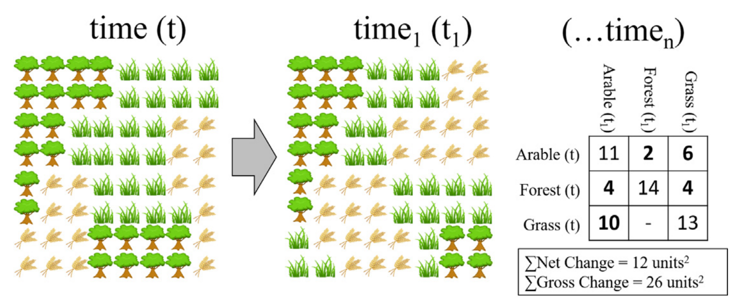
Samuel J. Tomlinson *, Ulrike Dragosits, Peter E. Levy, Amanda M. Thomson, Janet Moxley

Centre for Ecology & Hydrology, Bush Estate, Penicuik EH26 0QB, UK

HIGHLIGHTS

- Novel assessment of agricultural land use change in Great Britain (GB).
- Field-level land use data assessed on an annual basis, for nine years.
- Gross land use change analysed at a 25 m resolution for 70% of the GB land surface.
- Gross land use change in GB is, on average, 3 times higher than net change.
- Estimation of carbon fluxes using net and gross land use change data.

GRAPHICAL ABSTRACT



High-resolution, spatially explicit, field-level land use data provides **gross land use change** information which can have large impact on greenhouse gas fluxes.

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ABSTRACT

Land use change has impacts upon many natural processes, and is one of the key measures of anthropogenic disturbance on ecosystems. Agricultural land covers 70% of Great Britain's (GB) land surface and annually undergoes disturbance and change through farming practices such as crop rotation, ploughing and the planting and subsequent logging of forestry. It is important to quantify how much of GB's agricultural land undergoes such changes and what those changes are at an annual temporal resolution. Integrated Administration and Control System (IACS) data give annual snapshots of agricultural land use at the field level, allowing for high resolution spatio-temporal land use change studies at the national scale. Crucially, not only do the data allow for simple net change studies (total area change of a land use, in a specific areal unit) but also for gross change calculations (summation of all changes to and from a land use), meaning that both gains and losses to and from each land use category can be defined. In this study we analysed IACS data for GB from 2005 to 2013, and quantified gross change for over 90% of the agricultural area in GB for the first time. It was found that gross change totalled 63,500 km^2 in GB compared to 20,600 km^2 of net change, i.e. the real year-on-year change is, on average, three times larger than net change. This detailed information on nature of land use change allows for increased accuracy in modelling the impact of land use change on ecosystem processes and is directly applicable across EU member states, where collection of such survey data is a requirement. The modelled carbon flux associated with gross land use change was at times >100 Gg C y^{-1} larger than that based on net land use change for some land use transitions.

1. Introduction

1.1. Land cover/land use change

Alterations in land cover and land use on the Earth's surface, driven by human, societal and natural activities, are a global phenomenon that

* Corresponding author.
E-mail address: samtom@ceh.ac.uk (S.J. Tomlinson).

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can affect a wide range of activities and functions (Lambin et al., 2001). These include the sequestration and loss of ecosystem soil carbon (C) (Guo and Gifford, 2002), impacts on biodiversity (Pauleit et al., 2005; Newbold et al., 2015), conflicts in land use capability (Pacheco et al., 2014), impacts on greenhouse gas (GHG) emissions and sinks (Adger and Brown, 1994), and local (Chase et al., 2000), global (Feddema et al., 2005) and historical (Hansen et al., 1998) climate change. Being able to quantify land cover and land use change accurately is, therefore, of key importance for understanding effects of land use change and aid the design and implementation of climate change mitigation policy (Ostle et al., 2009; Sharmina et al., 2016).

Fluxes of GHGs between the biosphere and atmosphere are estimated and reported within the Kyoto Protocol to the United Nations Framework Convention on Climate Change, which requires countries to quantify and report annual GHG emissions from anthropogenic land use change. However, land cover and land use are not synonymous and much of the available data strictly represent land cover and not land use. Lambin et al. (2001) describe land cover as "biophysical attributes of the earth's surface" while land use implies application of human purpose and intent; for example a mature standing of forest is a type of land cover but the land use may be agricultural or recreational. Land cover can be determined from satellite imagery but the determination of land use (and whether associated GHG fluxes are anthropogenic in nature) requires additional information (Turner II and Meyer, 1998; NOAA, 2015). Both land cover and land use can be encompassed by the term Land Use and Land Cover Change (LUCC).

In Great Britain (England, Scotland and Wales), the annual quantification of GHG emissions from Land Use, Land Use Change and Forestry (LULUCF) are required as part of the UK Climate Change Act (Climate Change Act, 2008) and for international reporting to the EU and UNFCCC. The UK is fortunate in having a number of high resolution datasets available such as the Land Cover Map of Great Britain (Morton et al., 2011) and the National Forest Inventory/National Inventory of Woodland and Trees (Forestry Commission, 2002; Forestry Commission England, 2010). The Land Cover Map (LCM) is a detailed spatial land cover classification derived from Earth Observation (EO) data and the CEH Countryside Survey (CS) is a field survey for 500+ 1 km grid squares across the UK (Carey et al., 2008) but LCM does not distinguish land use where it is not synonymous with land cover (such as grazed or recreational grassland or arable crop type). This information is important, from a GHG emissions perspective, for quantifying nitrous oxide (N_2O) release from soils (Smith et al., 2011), C stocks building and depleting in soils and subsequent CO_2 sequestration and emissions from -grass-arable crop rotations (Paustian et al., 2000). Furthermore, LCM is only updated periodically (1990, 2000, 2007, 2015) which is not ideal for quantifying real changes such as crop rotations on agricultural land.

1.2. Agricultural land in GB

After emissions from the combustion of fossil fuels for energy, activities involving agricultural land are one of the biggest GHG sources in GB. GHG fluxes can occur from the losses and gains of soil organic carbon (SOC) through ploughing, crop residue incorporation and other practices, the release of N_2O from manure and fertiliser management and the tillage of soils, and methane (CH_4) emissions from livestock (Mosier et al., 1998; Rounsevell and Reay, 2009; Abson et al., 2014). Given that N_2O and CH_4 have global warming potentials many times that of CO_2 (298 times greater in the case of N_2O) (IPCC, 2006), coupled with the fact that agricultural area accounts for 70% of land area in GB (Defra, 2015a; Eurostat, 2016), it is evident that quantifying spatial LUCC patterns of agricultural land is key to reducing uncertainty in GHG emission totals in GB.

To enable this, it is crucial to supplement periodic datasets of known land cover information (e.g. LCM2007) with actual agricultural land use datasets. A time series of field-level data would allow for the quantification of spatiotemporal patterns of crop and field rotation in GB, which can be aggregated to the required level of resolution (Moxley et al., 2014). Such data exists in GB under the Basic Payment Scheme (BPS) as part of the Common Agricultural Policy (CAP) of the European Union.

1.3. Net vs. gross change and GHG inventories

When quantifying the fluxes in soil C, it is important to take into account not only the specific land covers/uses undergoing change, but also the dynamics of gross change across a time period rather than simply net change (Fuchs et al., 2015a). A net difference between two time steps will account for net gains and losses for given land cover/use types but will ignore the full range of changes occurring which could, potentially, lead to large underestimations of the area that has undergone a particular type of change. Net change does not reveal the detail of year on year change or bidirectional change between land use types (crop and grass rotations, for example) which is important for calculating GHG fluxes (Wilkenskjeld et al., 2014). A specific history for a given area of land based upon the finest possible temporal resolution gives the best approximation of legacy effects of C (and related GHG emissions) for that particular area (Fuchs et al., 2015a). Fig. 1 (Fuchs et al., 2015a) is a simple illustration of the possible differences between net and gross land use change.

Net land use change between two points in time may produce very different results, when utilised in GHG flux models, compared to the gross change equivalent (Fuchs et al., 2015b). Carbon stocks and GHG fluxes do not alter instantly at the moment of land use change but the timescale of adjustment can differ: losses of carbon from biomass and soil tend to be much more rapid than gains. Hence, the carbon stock loss (and subsequent CO_2 emission) from deforestation to grassland would be much greater than the carbon stock gain from the same area of afforestation on grassland over a single year (or 20 years). Levy and Milne (2004) give the example that 10 km^2 net afforestation could result from 50 km^2 of afforestation and 40 km^2 of deforestation. A GHG or carbon flux model making assumptions of 10 km^2 of net change of afforestation is likely to differ, in terms of results, from a model that accounts for gross changes and bidirectional change within the same

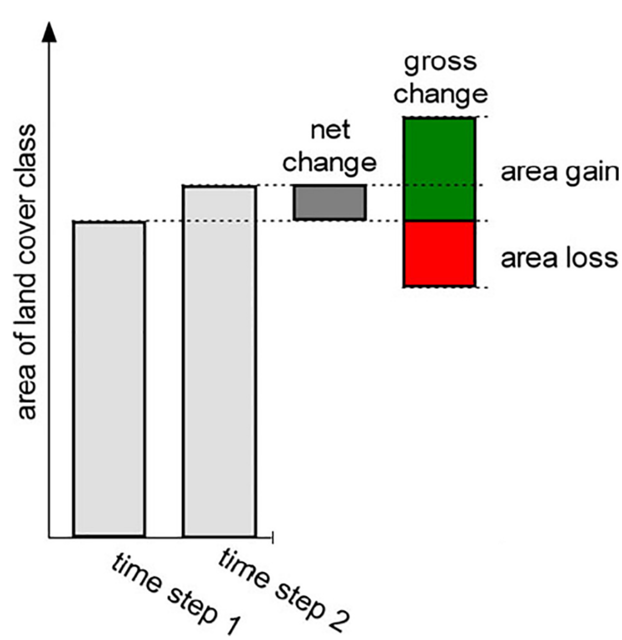

Fig. 1. Illustration of how quantities of net and gross land use change may differ between two time steps, from Fuchs et al. (2015a). Net change shows the difference in total area of land use between time steps while gross change is the sum of all area gains and losses for land use (for the same time step).

spatial context (Wilkenskjeld et al., 2014; Fuchs et al., 2015b). Due to physiological differences of crop types and soil types, dependencies on vegetation age and the specific crop/grass/forest rotations, GHG fluxes can be very locally dependent on land use (Abson et al., 2014; Drewer et al., 2012; Jeuffroy et al., 2013).

1.4. Aims

Previous studies in GB involving detailed LUCC data are scarce and cover a variety of topics: collaboration of land administration systems and land parcel systems (Inan et al., 2010); modelling infectious diseases (Flood et al., 2013); hydrology (Dunn et al., 2014) and impact assessments of environmental policy (Sagris et al., 2015). A majority of previous LUCC studies in GB at high resolution do not go beyond a single devolved administration (DA, e.g. Scotland or Wales) such as Smith et al. (2011), who produced an annual LUCC inventory with high resolution data for Scotland to simulate changes in soil and vegetation C.

The principal aim of this study is to quantify agricultural LUCC across the whole of Great Britain, on annual basis, for nine years and to assess the differences in net and gross land use change using a high resolution land use dataset at the GB scale – a novel analysis for GB. Secondarily, this study will investigate how these net and gross change differences may differ between land use categories. Finally, an assessment on the use of net and gross land use change for carbon flux estimations will be made using the data created within this study.

2. Methods

2.1. IACS data

Spatial polygon data used in this study was made available from the Integrated Administration and Control System (IACS), a European-wide, annual, spatially explicit dataset at the field level that serves as a register of agricultural subsidy claims under the CAP and is managed in GB by the separate devolved administrations (DAs) of England, Scotland and Wales. Land Parcel Identification Systems (LPIS) spatially represent the activities of farmers and their land, based on Geographic Information Systems (GIS), allowing area-based payments for geographic location and extent/type of the agricultural activity (Inan et al., 2010). The IACS was introduced across the EU in 1992 and reformed in 2003 as the Single Payment Scheme (SPS) which has, in GB, been replaced by a Basic Payment Scheme (BPS) in 2015 (EC, 2015; FAO, 2006; Smith et al., 2011). The level of detail in the IACS data varies between the countries of GB (details such as land use categories and specifics of codes etc.), but IACS essentially records field activity (cropping, grass types, forest coverage and more), field geometry and association to a farm holding. IACS data hold information on land cover (grasslands, crop areas, etc.) but also delineate these broad categories with land use information (such as type of crop, grassland age etc.). As the IACS data are an annual snap shot of agricultural subsidies claimed in GB, they are a very good indicator of agricultural land use in GB, particularly as the practice in GB is to plant on an annual basis (this may not be the case in other countries). Temporal coverage of IACS data obtained for this high-resolution LUCC study (Fig. 2) from England, Scotland and Wales differed from country to country but full GB coverage was 2005 to 2013.

The spatial coverage (Fig. 3) represents fields in the IACS system of crops, grasses and woodlands and, for 2013, agricultural land claimed under the SPS in GB was 95% of the total agricultural reported by the Department for the Environment, Food and Rural Affairs (Defra) for that year (Department for Environment, Food and Rural Affairs, 2015a, 2015b; Eurostat, 2016).

The level of detail in the data was country dependent but, in general, geospatial field boundary maps were provided in vector format (for use in a geographic information system) along with the coded land use and its geographical coverage for each code (as text or database tables). Field geometry and land use codes were joined by a common ID for every land parcel. The IACS data are considered disclosive (meaning that it is possible to identify individual farmers from the full dataset) so mapped outputs were produced at an agreed 1 km × 1 km resolution to preserve confidentiality.

2.2. Data processing

As a first step, the IACS data from all three administrations of GB had to be standardised due to their differing collection methods and data structures. For example, Welsh and Scottish data provided much more detail about individual arable crop types at the field level while English data reduced the amount of all land use categories from 54 in 2005 to 21 in 2013, creating both inter and intra country differences across the time series. Finer granularity of crop types or grass cover can be important when undertaking detailed studies into emissions from crop rotations as the inputs and outputs from vegetation growth and rotation differ between crops (Camargo et al., 2013). However, due to the nature of the collection of IACS data recorded through the SPS/BPS, human error can increase with increasing choice of response. The increased simplicity of crop, grass and forestry categories in England potentially allows for less error in the data but, consequently, the data may be less useful due to the limited categories recorded.

For GB-wide LULUCF studies it is necessary to reduce the number of land use codes in IACS data into aggregated land use categories and also to standardise the aggregated categories across all three countries to allow GB scale analysis. This aggregation of codes is primarily due to the fact that soil carbon parameters (used for modelling GHG emissions due to LUCC) are known for fewer land cover/use types than are represented by IACS data but aggregation also increased the efficiency of processing at the GB scale. To aggregate individual codes to land use categories, the IACS categories for all three countries were mapped using SPS and BPS handbooks and also expert knowledge. The land use categories were specifically selected for this study (and are closely related to IPCC LULUCF sector categories) and the number of IACS codes that were used for the category aggregations are shown in Table 1.

The increased detail of codes for crops in Scotland and Wales across the years is evident (Table 1) while 'uncategorisable' codes – mainly due to unknown meaning (i.e. not referenced in any handbook) or the large range of codes for non-vegetation related features such as roads and buildings – are removed. The area represented by uncategorisable codes is very small and there usually exists another claim code representing a crop or grass for the same field polygon, resulting in a small loss of data.

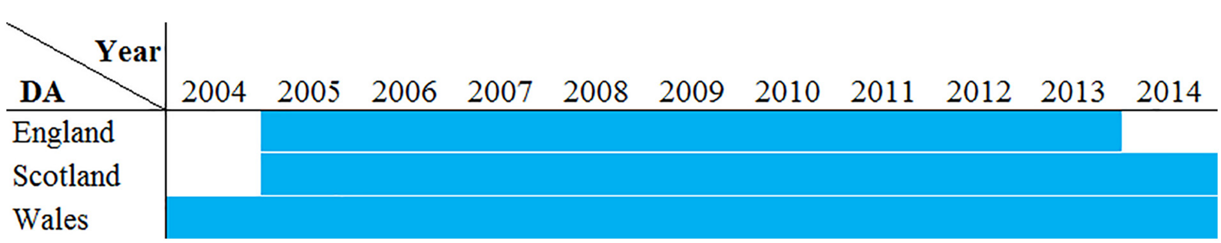

Fig. 2. Temporal coverage of Integrated Administration and Control System data per devolved administration in Great Britain in this study.

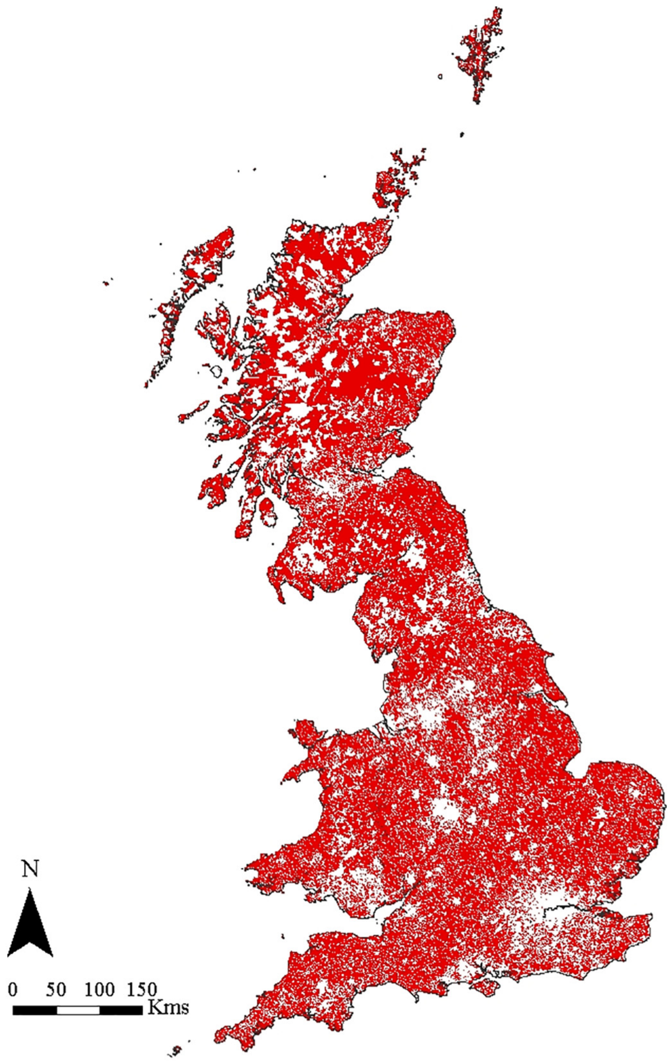

Fig. 3. Presence of Integrated Administration and Control System data in Great Britain (2013).

Following aggregation and the removal of uncategorisable codes, the data were processed to ensure a homogenous structure across the entire spatial and temporal range which meant the removal of extraneous, duplicate and unusable records. It is common in the SPS/BPS to submit not only field records with a solitary code but fields which contain more than one code (half forestry and half crop, for example) that may result in more than one aggregated category for a given field. For example, in Scotland the amount of fields in the raw data that have more than one code ranges from 17% to 29% across the time-series while in England the range is 12% – 25% across the time-series. The cumulative area of multiple categories in one field should not exceed the physical area of that field but information regarding multiple categories is redundant for LUCC analysis as the sub-field level spatial distribution is not known. Therefore it is required that each field polygon represents just one land use category and in instances where more than one category existed it was decided to utilise the category that had the biggest area represented in that field. However, the dominant land use category in a field (with more than one) has the potential to change dependent on the system of code aggregation. For example; a field with 40% forest, 30% wheat and 30% barley is classified as forest but after aggregation to forest and crop categories, the dominant category becomes crop (with 60% coverage). Furthermore, fields with multiple land use categories that sit around a threshold, e.g. 49% forest and 51% grass, would require a very small change (2%) to reclassify an entire area of potentially many km^2.

Table 1
Number of integrated administration and control system codes in each aggregated land use category, per devolved administration. Codes are aggregated from the entire time series and therefore do not reflect the amount of different codes for any single given year.

Aggregated category (this study)	Number of codes into each aggregation		
	England	Scotland	Wales
Arable crops (CA)	17	168	177
Perennial crops (CP)	13	33	46
Forest (F)	5	20	19
Grass not known (GNK)	2	2	0
Permanent grass (>5 years old) (GP)	7	16	19
Temporary grass (<5 years old) (GT)	7	21	17
Other (O)	0	2	5
Total number of codes across time series:	51	262	283

Raw data were put through a processing chain (Fig. 4); minor changes were made for each DA to suit the particular data structures. (See Fig. 5.)

Following data processing, an average of 87% of the spatial extent of the raw data was retained in the aggregated and standardised data per year (range 84–88%).

2.3. Data rasterization

Due to the large size of the datasets and the difficulties of analysing land use change with irregularly shaped polygon data (with frequently changing boundaries), all processed field-level IACS data were rasterized – that is converted from polygons to raster grids. One of the primary drivers for this decision, aside from computational savings, was to avoid the creation of sliver polygons. Sliver polygons are generated from small areas of overlap or gaps resulting from changes (real or error) in the overlay of two or more field geometries (Goodchild, 1987). Throughout time the boundary of a given parcel of land may change (e.g. due to merging/partition of fields, sale of land or even altered data-capture technique and errors etc.) which, over a number of datasets, can create very complex changing geometries to analyse. Rasterization allows for a standard grid with rigid spatial boundaries and a fixed cell resolution to be applied to all of the data throughout all of the time series, making change detection more straight forward.

However, rasterization will always result in a loss of accuracy of area and shape that is inherent to polygons due to the regular grid nature of rasters, especially at the perimeters of the polygons (Carver and Brundson, 1994; Liao et al., 2012; Wade et al., 2003). It was important, therefore, to choose a spatial resolution that provided a balance between computational intensity and the best possible retention of shape and area. Congalton (1997) suggests a spatial resolution of one-fourth of the area of the smallest polygon in the data but this would result in a GB-wide resolution of 5 m, a very accurate but computationally demanding resolution to work with. To attempt to adhere to the previously suggested approach to rasterization, the polygon data were represented in as much detail as possible with regards to individual field polygons and overall area. On this basis a 25 m × 25 m resolution was chosen which was one-fourth the area of 93% of all fields and represented over 99.7% of the total area of the processed data.

A visual comparison of land use categories in polygon (Fig. 5a) and 25 m × 25 m raster formats (Fig. 5b) shows the rasterization process has retained field shapes well and even features such as roads and the outline of the village in the centre. Furthermore, three 10 km × 10 km sample squares were randomly chosen (one in England, Scotland and Wales) to assess total area per land use category (km^2), prior to and following rasterization. It was found that the total area of each land use category (km^2) in the raster data was <1% larger/smaller than its vector equivalent, for all categories at all three sample sites (apart from perennial crops in Wales, which had a 4% error, due to its small area).

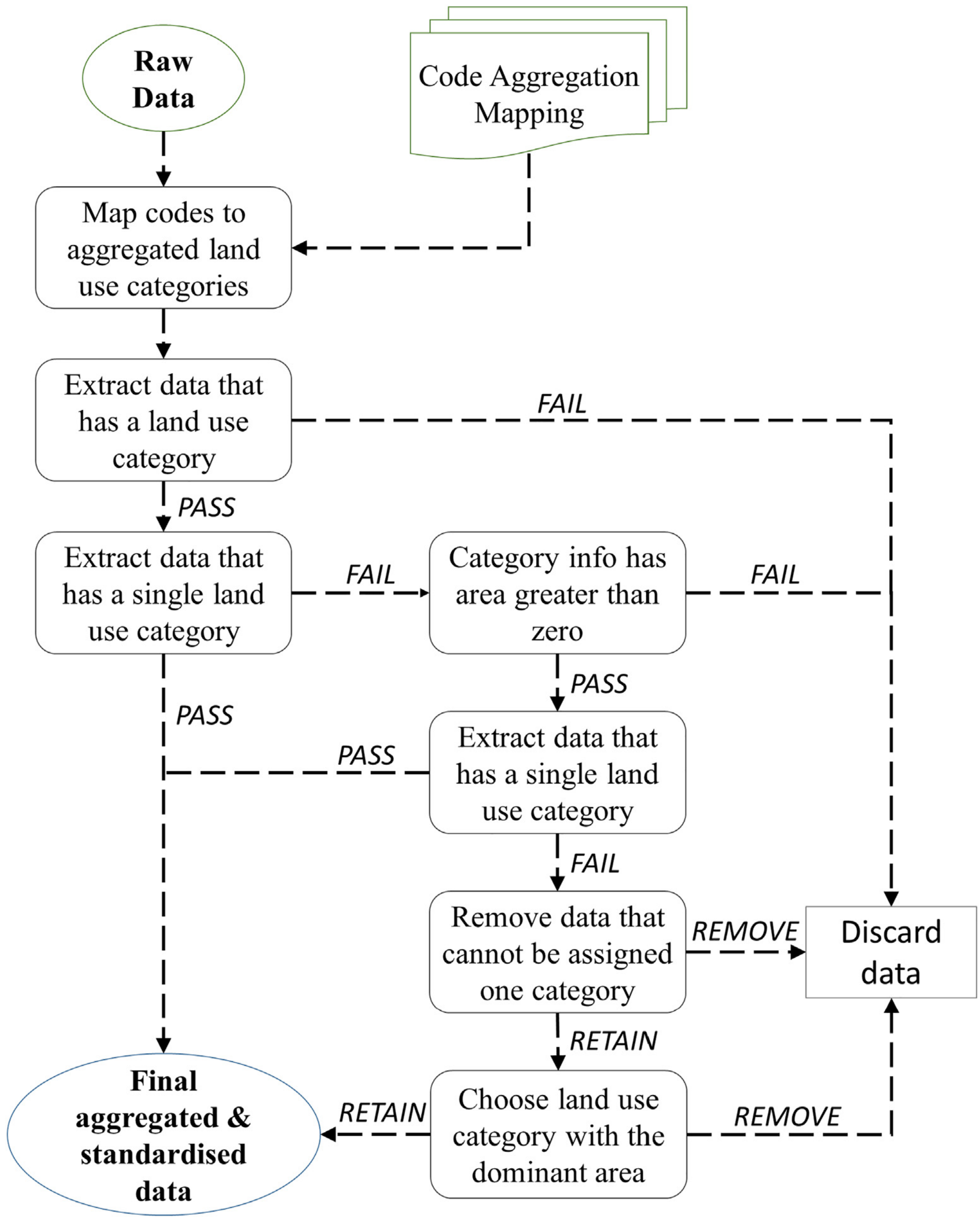

Fig. 4. Base methodology applied to raw Integrated Administration and Control System data for all of Great Britain to establish annual 'one field one category' datasets.

2.4. Land use change

Following processing and rasterization, land use maps based on the chosen category aggregations (Table 1) were made at a 25 m × 25 m resolution for GB (2005 to 2013). The year-on-year land use changes were analysed at a 25 m × 25 m resolution and non-spatially explicit change matrices were derived to visualise transitions between all land use classes (Penman et al., 2003). Change matrices were deemed to be the clearest way to show annual changes at a national level between 7 land use classes (i.e. 49 possible outcomes), for both gross and net changes between land use classes. An initial analysis based simply on the changing total area per category between years was calculated to assess the trends in the IACS data and is referred to as total area change. The total area change can encompass areas that become or come from areas of 'no data' and thus is not actual land use change applicable to C flux studies and/or greenhouse gas inventories but may be useful as secondary information for trend analysis.

For a given time step, the net change in the area occupied by each land use is given by the gross gains (the vector of column sums) minus the gross losses (the vector of row sums). Net change N can be extracted from a change matrix using Eq. (1);

$$N_U = \left|\sum_{i=1}^{n_U}\beta_{iU} - \sum_{j=1}^{n_U}\beta_{Uj}\right| \tag{1}$$

where N is the total change in km^2 (a positive value is net increase in land use, negative a net decrease), U is land use, i and j are the row and column indices (respectively), β is the land-use change matrix denoting the area changing from land use i to land use j and n is the area in km^2.

Furthermore, for years where annual data were available, gross change was assessed via the land use change matrices using Eq. (2):

$$G_U = \left|\sum_{i=1}^{n_U}\beta_{iU} + \sum_{j=1}^{n_U}\beta_{Uj} - \beta_{UU}\right| \tag{2}$$

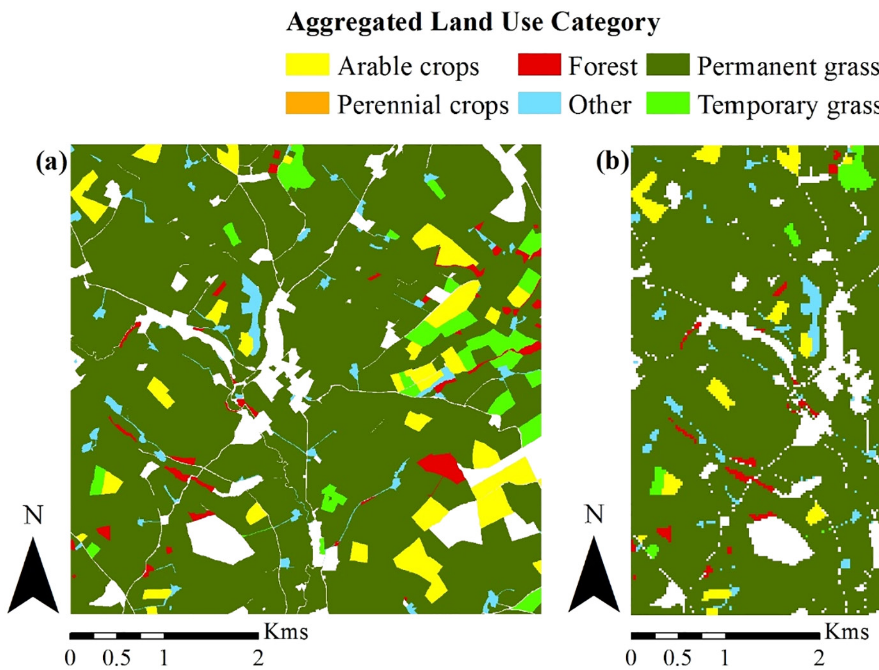

Fig. 5. A 5 km × 5 km sample of Integrated Administration and Control System (IACS) data for 2010, aggregated to land use categories, in (a) original polygon format and (b) 25 m × 25 m resolution raster format (example data randomly altered to comply with the data disclosivity agreement). Areas not covered by the IACS data are shown in white.

where G is the total gross change in km^2 for a change matrix for a given year. This is essentially the sum of area removed from a category (β_{iU}) and area added to that category (β_{Uj}), minus area that remains the same (β_{UU}). This was done at an annual resolution to ensure that only the gross/net relationship of the spatial information was assessed.

2.5. Soil carbon fluxes

We applied a simple empirical model of soil carbon fluxes following land use change, using the methodology described in Levy et al. (2017). The model represents the equilibrium soil carbon stock for each land-use class as a parameter. When land use changes, the soil carbon stock moves towards the equilibrium soil carbon stock for the new land use according to an exponential function. The rate of change is determined by a rate constant k for each transition. The flux of carbon over the time step is given simply by difference in the soil carbon stock.

The eight land uses classified in this study were aggregated to four classes (forest, crop, improved grassland and semi-natural/rough grazing) to match the classification used by Levy et al. (2017), based on Bradley et al. (2005). We performed the flux calculations using two data sets: (i) gross land use change identified by the IACS data, and, (ii) a degraded data set comprising only the areas where there was a net change in land use over the time span of the data set, i.e. defined as where land use differed between the start and end years (2005 and 2013). This thereby simulated the land use change that would be detected by an approximately decadal survey (such as Wood et al., 2017). This will generally provide an over-estimate of the extent of change that would be detected by such a survey, because the timing and nature of changes between 2005 and 2013 was retained. However, this provides the simplest case for comparison without applying arbitrary simplifications (e.g. assuming linear rates of change).

3. Results

3.1. Land use map from IACS data

The broad distribution of cropland and grassland can be seen clearly for 2013, (Fig. 6), with large arable crop growing areas along the eastern side of the UK and the grasslands prominent to the west and north, and parcels of forest scattered throughout the UK but especially in Scotland.

3.2. Land use change from IACS data

While a snapshot of land use for a single year is useful for some applications – such as ground-truthing satellite derived data – it does not give information on land use change occurring over time. In this study land use changes were assessed, starting with the total area change for GB (Fig. 7).

Annual differences in total area per land use category give an indication of the amount of land that is undergoing change from year to year (net change). Fig. 7 shows that Wales appears to undergo less net change than both England and Scotland but there is no information regarding what the land use is changing to or from, i.e. gross change. A change matrix (Fig. 8) shows both net and gross land use changes (the land use change matrix does not include data where any cell has "no data" in either year). As an example, there were 156,322 km^2 of data available for 2012 and 154,832 km^2 of data for 2013, resulting in 150,830 km^2 of land use change data for 2012/13 (Fig. 8). By comparison, Defra (2014) and Eurostat (2016) report a total Utilised Agricultural Area (UAA) for GB of 161,440 km^2 for 2013.

In GB as a whole, land parcels recorded as permanent grass (GP) in 2012 and remaining so in 2013 accounted for 80,482 km^2 (53.3%) of known activity in the IACS dataset. Overall, agricultural land remaining the same from 2012 to 2013 accounted for 144,868 km^2 (96%) while the biggest known change in agricultural land use at GB scale was arable crops (CA) changing to temporary grass (GT) (1596 km^2, 1.1%), followed by temporary grass changing to arable cropland (1194 km^2, 0.8%).

Fig. 9 shows the eight largest mean changes in GB across the time series where data are available for GB (i.e. eight time steps from 2005 to 2013, ordered by mean change in km^2).

Rotations of arable crops and temporary grasses constitute the largest terms (CA to GT – mean c. 2000 km^2; GT to CA – mean c. 1800 km^2) while all eight of the largest terms involve arable crops and/or grassland (Fig. 9).

Overall, the area of land changing use is small compared to that which does not change; roughly 92% of land use activity derived from

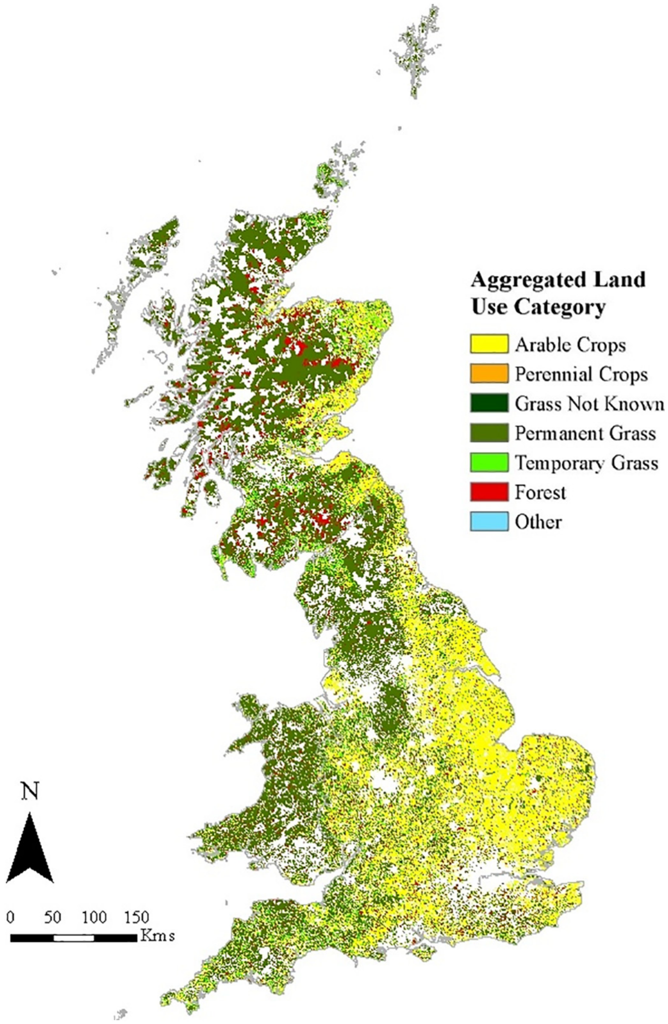

Fig. 6. Land use data derived from Integrated Administration and Control System (IACS) data, for 2013, for Great Britain. Areas not covered by the IACS data are shown in white.

IACS data in GB underwent no change in 2005/06, a figure which steadily increased to 96% in 2012/13.

3.3. Sub GB-level change trends

A change matrix holds no explicit spatial information apart from the total area it represents. It is well known that farming practices are heavily influenced by factors such as climate, soil type, agricultural policy, altitude and even scale of operation (OECD, 2009; Rounsevell et al., 2003) and so land use change can be expected to contain spatial variation. At the country level, permanent grass remaining as permanent grass is as high as 88% of the IACS derived activity in Wales (2005/06) while in England unchanged arable cropland is the primary activity at 46% (2012/13). In the UK this may be expected due to the drier, warmer climate in the south-east of England (favouring arable crops) compared to the cooler, wetter climate in south Wales. In terms of change, rotations of arable crops and temporary grassland remain the largest agricultural land use change activity in England and Scotland but in Wales the rotation of permanent grass (with either other grasses or arable crops) provide the biggest change from 2005 to 2013. Therefore, differing quantities of actual change exist at the sub-national level and may become more pronounced the smaller the spatial unit (e.g. county to county etc.).

Extracting the amount of land use change per DA, as a percentage of all activity for that DA derived from the IACS datasets, shows differing amounts of change per country (Fig. 10). Across the timeline, Wales generally shows the smallest relative change per year and also the smallest inter-annual range, likely due to the dominance of permanent grassland and the presence of large areas of upland grazing, while England has shown a decline in change from 10.8% in 2005/06 to 4.2% in 2012/13.

This decline in actual change (change where data is present in a cell in both years and not simply changes in total area) in England was due primarily to a steep decline in the amount of land changing from arable crops to temporary grass between the years 2005/06 and 2007/08 (offset slightly by an increase in the opposite direction), and then a 67% reduction in the area of temporary grass changing to arable crops in 2008/09. Gross land use change activity at the 25 m × 25 m resolution (binary outcome; actual change or no change/no data) was aggregated to a 1 km × 1 km resolution (as change in $km^2\ km^{-2}$), summed for all years from 2005 to 2013, and mapped for GB in (Fig. 11). Of the c. 230,000 1 km × 1 km cells in GB, c. 150,000 km^2 (65%) contain some change across the time series, representing a vast majority of the IACS data coverage (range 0.01 $km^2\ km^{-2}$ to 5.4 $km^2\ km^{-2}$). Of these cells, 9% have >1 $km^2\ km^{-2}$ of gross land use change, from 2005 to 2013.

The highest levels of change in Scotland are due to the rotation of large permanent grass and forest land parcels (possibly tree planting or deforestation) while in England the areas of highest change are crop and grass rotations.

3.4. Quantification of net vs. gross change

Quantification of net (Eq. (1).) and gross (Eq. (2).) land use change (in km^2) for GB for all pairs of consecutive years from 2005 to 2013 was undertaken (Fig. 12). Total area change – changes including areas of no data in one of the years – was not calculated due to its redundancy in C flux models.

Across all pairs of consecutive years in GB, the gross:net total area ratio ranges from 1.5 (2007/08) to 6.6 (2010/11) (mean = 4). A gross:net area ratio was derived to standardise the gross:net relationship and estimate the magnitude of the underestimation of the net change approach (Fuchs et al., 2015a). The lowest quantities of net change (977 km^2) and gross change (5953 km^2) occurred in 2010/11 and 2012/13 respectively. Large rotations between arable crops and temporary grass were the primary driver for the gross change figures. This gross change would not be reflected in the net change if the areas of the two categories in rotation are similar. The spike in net change in 2007/08 was driven by large areas of grassland converted to arable crops in England and Scotland with much less change in the opposite manner. Fig. 12 shows that not only do gross change estimates reveal much more land use change activity than net change but that the amount of gross change varies from year to year, highlighting the importance of using land use data at the highest spatiotemporal resolution.

Furthermore, net and gross change equations were also applied at the individual land use category level and gross:net area ratios were derived – these range from 1 (forest in Scotland, 2006/07) to 369 (permanent grass in Wales, 2010/11) (Fig. 13). These ratios are calculated by assessing how much land is lost from given land use category added to how much land is added to the same land use category, against the net change. Forest often has a lower ratio while the high ratios of temporary grass and arable crops in England highlights the rotational pattern of these categories that net change estimates do not identify. It should be noted that these totals per land use category are stand alone and should not be added together due to double counting and are useful in highlighting the variability of gross:net ratios between land use categories.

3.5. Soil carbon fluxes

When applied to the calculation of soil carbon fluxes associated with land use change, we see that using gross land use change inevitably

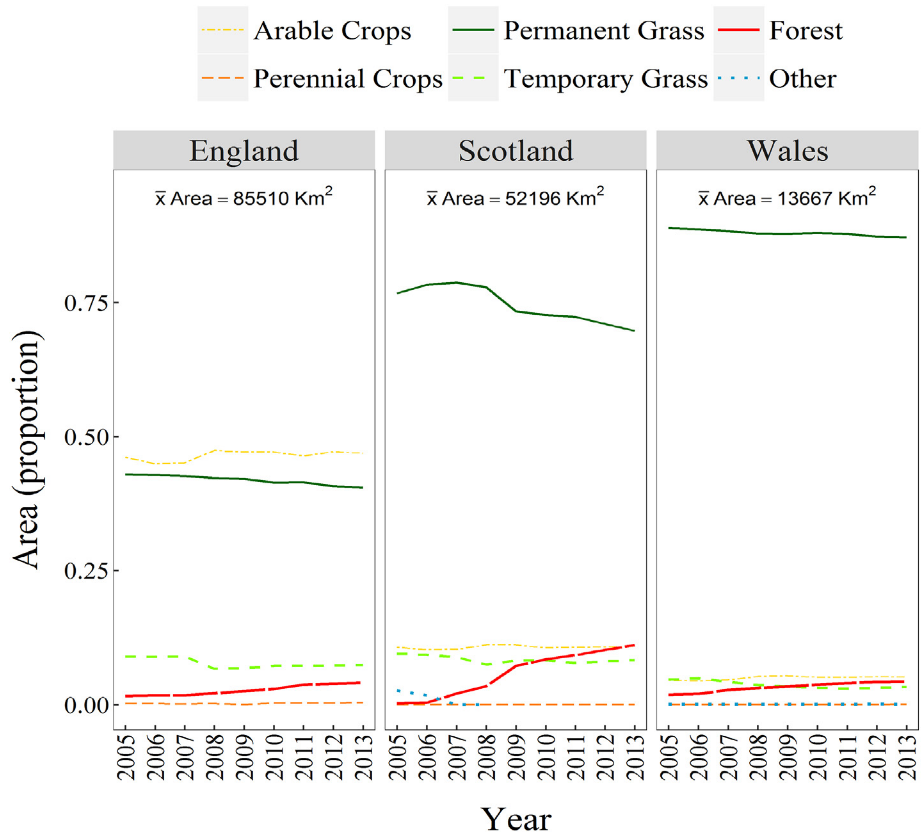

Fig. 7. Proportional area of land use categories for GB, of total area of data per country, derived from Integrated Administration and Control System data, 2005 to 2013. Mean total area of land use (km^2) across the time series is given per country.

produces a larger carbon flux in each category (greater positive or negative values, Fig. 14). This is simply because a greater extent of land use change is recognised: by definition, any areas that had the same land use at the start and finish (and so showed no net change over the period) are excluded from the calculation for net land use change.

In the case of forest land, this makes very little difference, because most conversions to forest are long-term, and remain as forest for the rest of the period. In the case of cropland, this makes a very large difference, >200 Gg C y^{-1}. This is because many conversions to cropland are short-term, and are converted back (mainly to grassland) within the nine-year period. All carbon fluxes associated with these changes would be missed by a decadal survey which detects only relatively long-term change.

2012 \ 2013	CA	CP	F	GNK	GP	GT
CA	45,794	28.2	17.2	321.5	216	1,596.4
CP	9.7	302.8	1.8	0.7	3.1	1.8
F	6.2	1.3	8,842.3	2.8	189.1	6
GNK	120.5	0.9	3	305.9	31.2	18.6
GP	621.3	3.8	412.4	28.9	80,482.3	430.6
GT	1,194	2.5	14.5	6.2	660.7	9,140.9

Fig. 8. Land use change matrix, 2012 to 2013, for Great Britain (km^2); CA = Arable crops, CP = Perennial crops, F = Forest, GNK = Grass not known (i.e. no distinction between temporary and permanent grassland), GT = Temporary grass and GP = Permanent grass. Category O (Other) is not shown here as it was <0.1% of all net and gross change.

4. Discussion

4.1. Differences in gross and net change

The principle aim of this study was to identify and quantify the potential difference between gross and net land use change derived from a dataset with high spatiotemporal resolution. From 2005 to 2013, there was c. 63,500 km^2 of gross land use change in Great Britain compared to c. 20,600 km^2 of net land use change, producing a gross:net ratio of 3.1 for all of GB for the whole time series. The gross:net ratios for all categories across GB (Fig. 13) also highlight the amount of extra information gained from being able to estimate gross change. For example, in England in 2006/07, all changes involving arable crops and temporary grass (not exclusively between the two) produced 6900 km^2 of land use change whereas the sum of net change of the two categories was only 200 km^2. Changes involving arable cropland consistently accounted for 70% to 80% of gross change in GB from 2005 to 2013 and while this rotation of arable crops, usually with temporary grass areas, is somewhat expected from an agricultural dataset, it has not been quantified previously. Bi-directional rotation of arable crops and temporary grass has been shown to be the dominating change in GB from 2005 to 2013 but both change directions show a large range in values (Fig. 9). This is due to a decline in rotation patterns, particularly in England, between the time steps of 2005/06 and 2008/09 and may be tied to a sharp increase in Single Payment Scheme claims for arable land left out of production from 2006 onwards under the Good Agriculture and Environmental Condition standards (Defra, 2008; Defra, 2011;

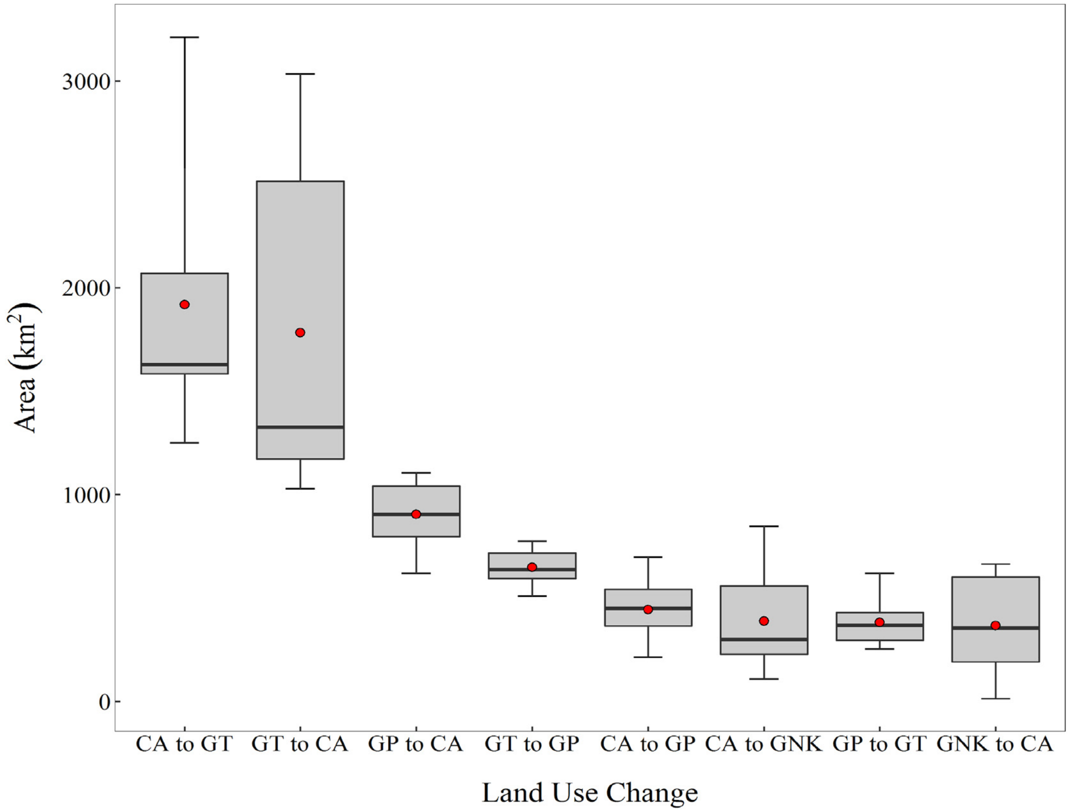

Fig. 9. The eight largest mean land use changes in Great Britain across eight time steps (km^2), from 2005 to 2013; box and whisker (grey/black) showing minimum, maximum and quartiles; mean (red dots); CA = Arable crops, GNK = Grass not known (i.e. no distinction between temporary and permanent grassland), GT = Temporary grass and GP = Permanent grass. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Department for Environment, Food and Rural Affairs, 2015a, 2015b). Other possible drivers for these reductions in gross change may be the global food crisis of 2008, the causes of which are complex (Baltzer et al., 2008; Piesse and Thirtle, 2009; Trostle, 2008), and also a stagnation of cereal imports to the UK from 2005 to 2007 (Defra, 2014). The decline of cropland areas changing to grass may reflect an attempt to address

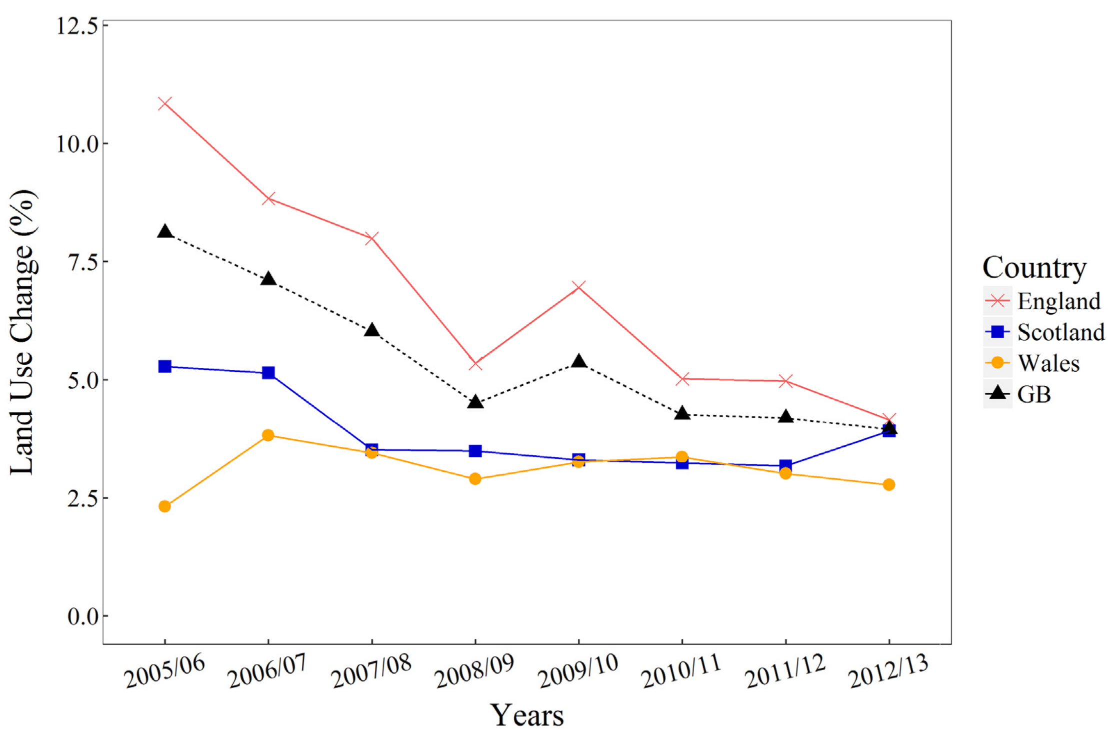

Fig. 10. Land use change as a percentage of all area derived from the IACS datasets, where data exists in both change years, per devolved authority of Great Britain (GB). Change for GB (triangle and dashed line) is an area-weighted average.

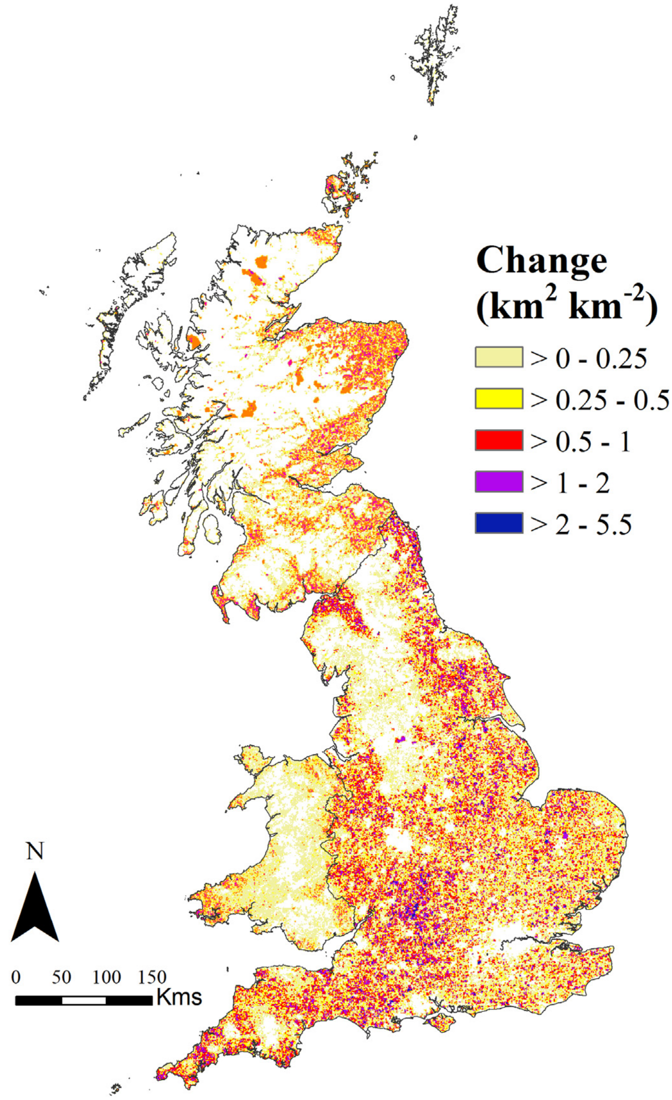

Fig. 11. Sum of gross change per square kilometre (as km^2) from 2005 to 2013; derived by aggregation of 25 m grid resolution data in every 1 km^2 for every change year. 'No change' is land that has remained the same category or areas with No Data (in either or both years). Areas not covered by the IACS data are shown in white.

the need for increased production and sharply increasing food prices up to 2008. It is unclear how much arable land is likely to be abandoned in the near future following intensive agriculture, but the EU CAP provides financial support for land managers to ensure that they maintain land in Good Agricultural and Environmental Condition to provide a strong disincentive to the abandonment of agricultural land.

4.2. Importance to greenhouse gas inventories

As shown (Section 3.5), the extra land use change information that can be generated by gross change calculations with the IACS dataset in GB is of significant benefit for calculating fluxes for greenhouse gas inventories, due to the detailed spatiotemporal resolution that allows for quantification of bi-directional land use change. Fig. 12 demonstrates the detailed information that can be gained by using a gross change approach; land parcels changing from crops to grass and vice-versa may all carry specific rates of C flux for an inventory model which a net change approach may interpret as zero. Fig. 14 highlights the potential difference gross land use change makes to C flux estimates in an inventory model, across land use types. Agricultural land represents the majority of land use in the UK, and there are currently no annual land use datasets that specifically represent agriculture within the LULUCF framework. IACS data allow for very detailed land use maps and land use change analysis with, on average, 152,300 km^2 (67%) of Great Britain represented by vector data (rasterized to 25 m × 25 m resolution) from 2005 to 2013. These high-resolution data not only allow for more accurate reporting to environmental protocols but also provide an indication of response to policy, such as reforestation (Defra, 2013).

Land use information that cannot be used for gross land use change analysis such as this one (due to 'no data' in either of the change years) is still viable information for inventory modelling in LULUCF (Thomson et al., 2013). The data can be put into the larger model alongside other sources of data (such as CORINE and the National Forest Inventory) to further inform the land use history of a given cell. The differences in net change and total area change (Fig. 12) are therefore not necessarily lost information.

IACS data on forests and woodland only relates to on-farm woodlands so does not include other GB forests. Forest is therefore spatially far less prevalent in the IACS data than crops or grass, but is an important land use category in land use change analysis and particularly for flux modelling due to the relatively high soil carbon stocks associated with woodland and high above and below ground biomass C stocks (Dixon et al., 1994). These make loss or gain of woodland the large sources and sinks of C per unit area (Cannell et al., 1999). Total gross change involving forestry in GB (from agricultural land registered in the SPS) had a mean value of 644 km^2 from 2005 to 2013 (range 470–965 km^2) compared to a net change mean of 262 km^2 (range 32–647 km^2). The mean gross:net ratio of 4.6 across the time series (range 1.5 to 16.6) is lower than arable crops and grasses (Fig. 12) but potentially more influential to carbon flux models.

4.3. Spatiotemporal heterogeneity

As mentioned throughout, estimated quantity and characterisation of change (total area, net or gross) is dependent on spatial scale but it is clear from this study (Fig. 6; Fig. 11) that the spatial distribution of change is heterogeneous to finer spatial scales. This heterogeneity may be linked to many factors including soil type, climate, topography, economics, policy, transport, historical reasons and even personal preference (Gilchrist Shirlaw, 1966; O'Kelly and Bryan, 1996). Furthermore, quantities of change in a given space may vary through time (due to rotation patterns, economic drivers etc.) meaning net/gross change is ideally calculated at the finest spatiotemporal resolution possible.

As an example, a 2500 km^2 area in the central west of Scotland, spanning the regions of Argyll and Perth, is an upland area that typically exhibits <1% change of its total land area as derived from the IACS data across the 2005 to 2013 time range. The local-scale quantities of change are much lower than the Scottish average (Fig. 10) but the annual temporal resolution reveals two instances where quantity of gross change is above 4%, information that would perhaps be missed altogether should coarser resolution data (temporally) be used – an occurrence that may happen many times over the whole UK.

4.4. Artefactual change

Land use changes, in this study, were determined from the conversion of pixels from one land use category to another. The central assumption is that the annually recorded land uses in the data truly represent reality and that the aggregated land use codes minimally distort these data. However, there are three primary issues that may produce inaccurate estimations of change and the creation of 'artefactual change': input level error, methodological subjectivity, and policy driven data records.

The first, input level error, refers to errors in the recording and/or construction of the data; either by farm-holders inputting data incorrectly (e.g. incorrect land use or incorrect area), errors in the transfer

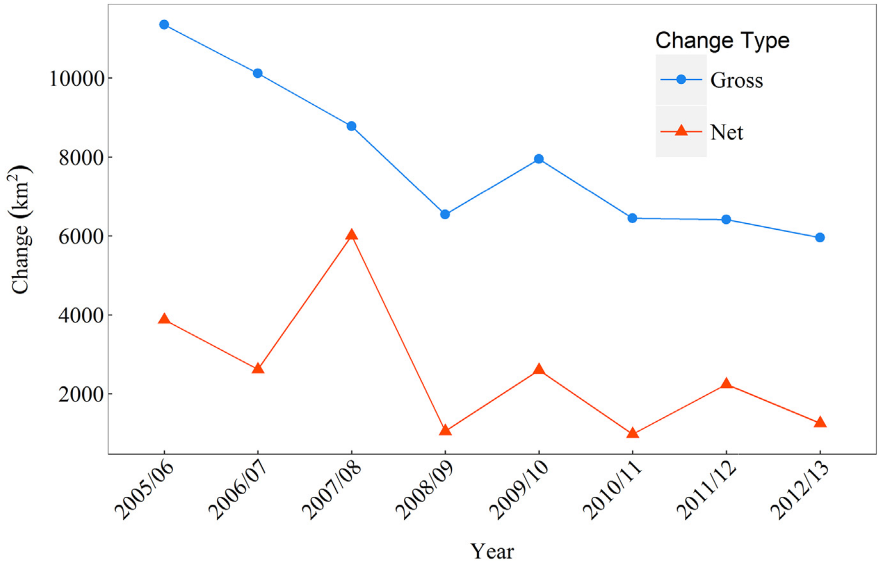

Fig. 12. Annual gross and net land use change in Great Britain from 2005 to 2013; total gross area (km^2) is the sum of all off-diagonal elements in the change matrix (Eq. (2)) while net change (km^2) is total area difference between years, disregarding no data cells (Eq. (1)).

of field level data into databases or errors and changes with regard to the spatial geometries of the field parcels themselves. These input errors can result in land use changes that are not real. All of these factors are beyond the control of studies such as this one and, in total, are estimated to be very small at the UK-scale.

Secondly, methodological subjectivity refers to steps taken during the transformation of the original data into a standardised form. There are some issues with regards to the data cleaning process, such as land use codes in the raw data that do not exist in the accompanying handbooks, but the most prevalent is the process of ensuring a field parcel

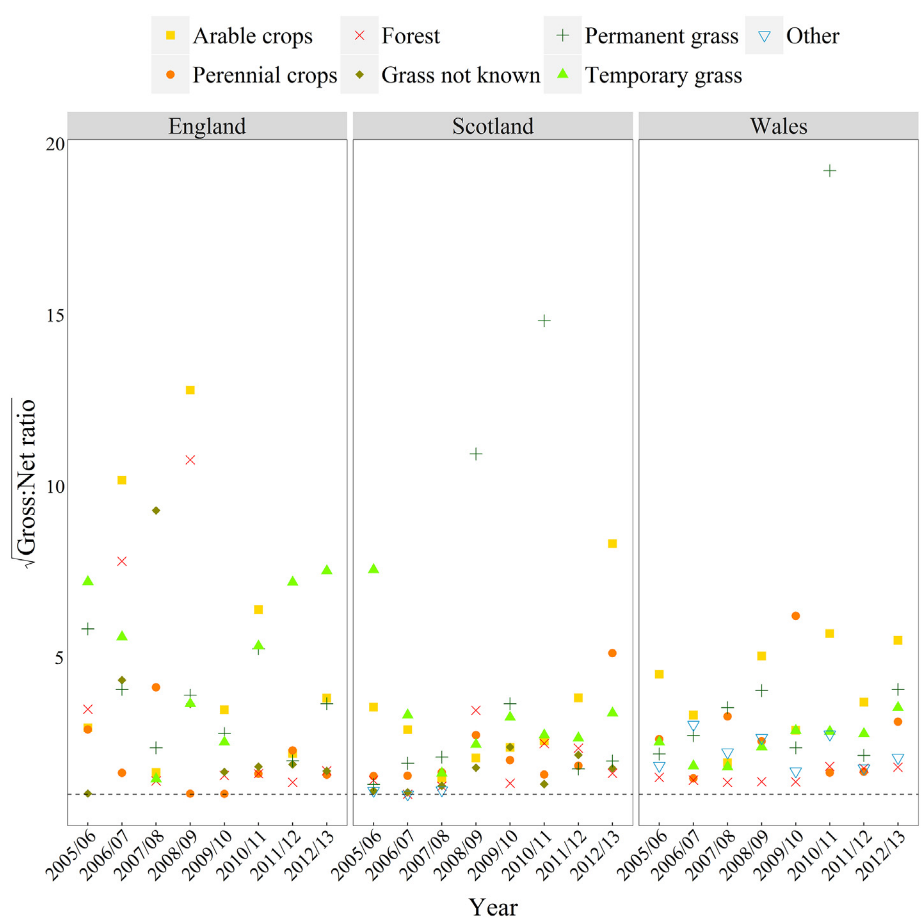

Fig. 13. Square root transformation of gross:net ratios per land use category per year, for each Devolved Authority in Great Britain. The dashed black line represents a gross:net ratio of 1 (i.e. full identification of all land use change by net change).

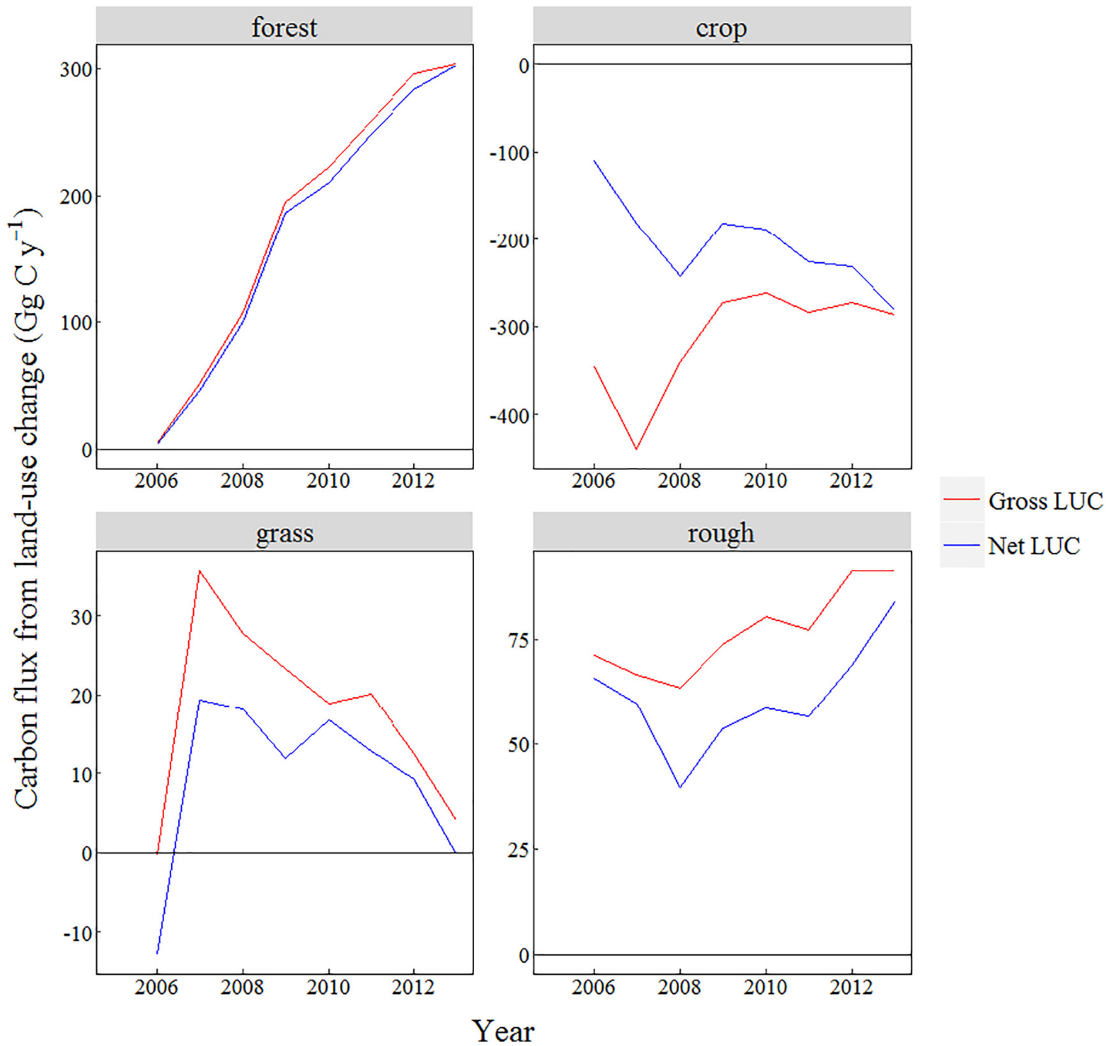

Fig. 14. Carbon flux (Gg C yr^{-1}) generated by land use change across four aggregated land use categories based on gross land use change information (red) and net land use change information (blue). Positive values are sequestered C and negative values are emitted C (equilibrium is represented by a horizontal black line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

represents only one land use category. To obtain this uniform land use per field, sub-parcel claim data must be aggregated/discarded to retain one representative land use category. A subjective decision was made that the representative category of a given parcel (where categories present were >1) had to be the largest in that parcel. In theory, that land use category could be <50% for some sub-parcel claims. As shown in the methodology, up to 29% of land parcels (by number, country dependent) had to undergo this process. Another element of methodological assumption was the system of code aggregation to a) create a homogenous land use code set across all four agricultural subsidy systems of the UK and b) reduce the data from many tens of codes to seven for this study to allow for easier land use change analysis and harmonisation into current UK GHG and carbon flux assessments (such as the LULUCF sector inventory). Both of these assumptions (parcels with a single use and the code aggregation) influence how the final land use data are created and thus the quantities and type of land use change between years.

Finally, artefactual change may arise from policies enacted at government level that influence how land use is recorded as well as how the land is used in reality. The primary example is the recording of forests in the IACS data where the total area of parcels claimed as forests in GB have increased from c. 1700 km^2 (2005) to c. 10,000 km^2 (2013), with a sharp increase in Scotland after 2008 (Fig. 15).

While this large increase may be, in part, a response to reforestation and woodland grant schemes within the UK (reflecting actual land use modifications driven by policy), it is more likely due to the adjustments of policies such as the Common Agricultural Policy (EC, 2008) which allowed for compatibility between woodland schemes and the SPS, effectively allowing for dual claims for the same land from the Forestry Commission and SPS (Forestry Commission England, 2010). Prior to this EU-level policy shift, land converted to woodland under the Farm Woodland Premium Scheme, the Scottish Forestry Grants Scheme, the Woodland Grant Scheme and the English Woodland Grant Scheme were eligible for SPS payments as far back as the 2006 claim year (Defra, 2005). It is unlikely that all of the increase in forested land parcels in the IACS datasets are 'real' shifts in land use but it is difficult to know how much total area change is purely down to grant schemes and how much is real forest growth. For example, of the 3768 km^2 of forest claimed through IACS in Scotland in 2009, 45% is unchanged forest from 2008 and just 2.7% and 0.1% changed from grass and arable respectively. The remaining 52.2% of forest in 2009 (1958 km^2) came from land not known to the IACS dataset in 2008, suggesting much of the increase in afforested area in the IACS data is from changes in how the land is claimed/recorded and not from real change. Further data sources, such as the National Forest Inventory and the various Woodland Grant Schemes in GB (data not available for use in this study), would allow

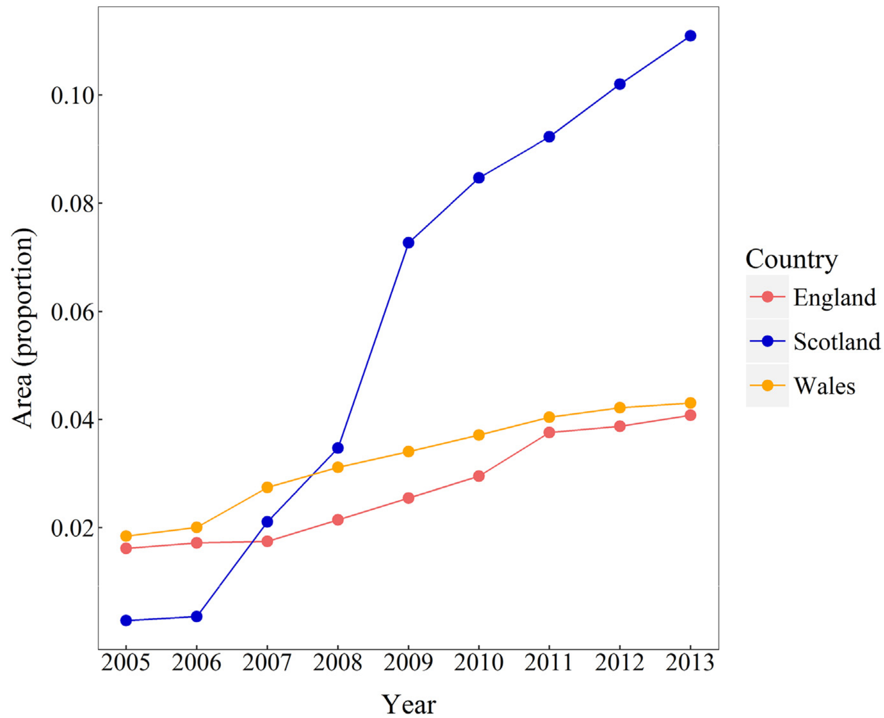

Fig. 15. Total area (km^2) of land parcels recorded as forest in the Integrated Administration and Control System data in England, Scotland and Wales from 2005 to 2013.

us to assess how much of the increase is an artefact of changes in IACS recording versus actual afforestation or reforestation. Furthermore, afforested land is commonly defined by planting date and, as such, may cover a large range of tree ages and sizes and may present problems or uncertainty in a simple land use change model. This makes the total gross change, for forested land in particular, a lot less certain than cropland and grassland activities and highlights the importance of using multiple input datasets (such as the National Forest Inventory which contains information such as planting date to aid C flux models) when creating a land use history for flux modelling. A similar hypothesis can be put forward for the double peak in gross change in Argyll and Perth outlined above – is this real land use change or the maturation of trees to a certain age that appear as a change from grassland to forest in the data but in reality are just slightly older trees.

5. Conclusions

This study has analysed agricultural field level data from the Integrated Administration and Control System to map agricultural land use (static in time) and to quantify the differences between net and gross land use change in Great Britain for the first time and their potential effect on soil carbon fluxes. When considering gross rather than net land use change, this study estimated that there is roughly three times more gross than net land use change (area, km^2) from 2005 to 2013 in GB. This information can be applied in carbon flux models and be used to more accurately estimate greenhouse gas emissions from agricultural land; around 3 times the amount of sequestered C was estimated in 2006 on cropland using gross land use change compared to net. This highlights not only the importance of gross change estimates for such models but also the importance and utility of high resolution spatiotemporal data such as the IACS datasets.

Land use change on agricultural land in GB is heterogeneous throughout space and time: Gross change from crop rotations, for example, are dependent on factors such as climate and soil type resulting in spatially variable land use change and the magnitude of change in a given location may vary throughout time based on external factors such as market demand or policy.

Large datasets made from field level records such as the IACS data used in this study can help to produce detailed land use change information at the national scale and can be used alongside other datasets such as CORINE, the National Forest Inventory (for the UK) and the Land Cover Map of Great Britain to produce more accurate land use/cover maps both spatially and temporally (Levy et al., 2017). It would be beneficial to have other land use datasets, such as CORINE, on an annual resolution to allow for similar comparative studies from different data sources but such data are not available at this time.

The most problematic land use categories within the IACS data are those concerning the representation of forest and woodlands, due to possible errors produced by policy change, the binary nature of aggregated land use codes (grass or forest) and also data cleaning. It is important to recognise these issues and use IACS data in tandem with other datasets to produce the most accurate land use timeline possible. In this study, land use categories were aggregated for ease of use and to broadly reflect those categories used in the LULUCF model of GB, but the detail of the data is such that if more parameters were to be introduced for flux modelling (i.e. for an increased number of land use change combinations) then the data could be reanalysed to incorporate these changes.

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Conflicts of interest

The authors declare no conflict of interest.

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