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Rural land use in England and Wales between 1930 and 1998: Mapping trajectories of change with a high resolution spatio-temporal dataset

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Abstract

In this paper I present a method to analyse the spatial and temporal characteristics of land use change at representative sites in England and Wales between 1930 and 1998. Multiple data sources have been integrated to provide an estimate of land use change at 23 randomly located sites for 6 time-steps ranging from 1930 through to 1998. The method is called 'stability mapping' and exploits the spatial data handling capabilities of Geographic Information Systems (GIS) to pinpoint those specific areas of individual sites most prone to land use change. It involves the calculation of three indices: similarity, turnover and diversity as well as the detailed analysis of trajectories of change. An assessment is made of the impact of changing spatial and temporal resolution on the behaviour of these metrics and recommendations on their use are offered. The approach as outlined would be equally applicable in other locations where good quality historical map data are available.

Keywords: Historical data; Land use change; Land utilization; Rural landscapes; Time series

1. Introduction

During the 20th century the rural landscapes of England and Wales have undergone significant change, both in form and function, as the economy and needs of society have developed. Although nearly 90% of the population of the two countries live in urban areas (Denham and White, 1998) the vast proportion of the land surface is still farmed and therefore, rural in nature. In common with many countries in mainland Europe, changes in rural land use, arising from agricultural practices in particular, have impacted deleteriously on the quality of the landscape (Westmacott and Worthington, 1974) as well as the biodiversity of the countryside as a whole (Skinner et al., 1997; Krebs et al., 1999; Donald et al., 2001; Robinson and Sutherland, 2002).

Research interest in the study of rural land use change is longstanding in England and Wales, with much seminal work on the topic undertaken during the 1930s by geographers such as Dudley Stamp of Kings College, London (Stamp, 1931, 1932, 1947). This interest was renewed during the 1960s by work undertaken by Robin Best who provided incisive commentaries on the changing nature of Britain's land use whilst work undertaken by Terry Coppock detailed changes in the agricultural framework of England and Wales (Best and Coppock, 1962; Coppock, 1964, 1968; Best, 1981). More recent studies by Sinclair and Bell (1983) which focused on the upland areas of the country were complemented by a large project undertaken by Huntings Surveys (1986) which provided summarised land use change data for three dates between 1945 and 1980. This was further extended by Sinclair (1992) who attempted to provide a synthesis of existing data in order to provide 'broad-brush' statistics on shifts in major land uses in England and Wales.

Between them, such studies have highlighted important trends in national land use change. Most significant of these were: a gradual loss of mixed farming with geographic polarisation of grassland in the west and arable in the east; expansion of villages and towns, especially those within commuting distance of larger urban areas; significant increases in the area of managed forest (James, 1981); the loss of semi-natural habitats such as heathland due to reclamation (Parry, 1982).

Conceptually, land use change studies form a type of time-series analysis, where the object of interest (land use) is being sampled at discrete intervals which are often not regular

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(Hammond and McCullagh, 1986; Diggle, 1990). In addition, the successive observations are not statistically independent and the order of observation remains critically important (Chatfield, 1996). Most typically, these data take the form of time-slices, linked by spatial co-registration within a GIS (Langran and Chrisman, 1988; Langran, 1992; Peuquet, 1994). Work on the construction of temporal topology in GIS and appropriate tools to access and query such data is still ongoing (Dragicevic et al., 2001; Marceau et al., 2001), but it remains a significant challenge—both conceptually and technically. With each new time-slice that is added, additional complexity is introduced.

The technical challenges posed in the construction of robust spatio-temporal databases can move the focus of attention away from the map as the unit of analysis and blur the need to focus on the process of change. The map remains key to such understanding and methods which unlock the patterns which can reveal process are helpful (Kienast, 1993). Flawed as historical land use maps may be, with sensitive handling they remain rich in detail and a map-based analysis of changing patterns of land use can reveal much of value (see examples provided by Skånes and Bunce, 1997; Cousins, 2001; Van Eetvelde and Antrop, 2004; Bender et al., 2005). Such emphasis has been strongly encouraged by recent work by Käyhkö and Skånes (2006), whose research in Scandinavia has exhorted the need to think about the process of change, how it is expressed on the ground and ultimately what it might mean for rural landscapes and the communities dependent upon them.

To this end, a stratified sample of $23 \times 1\,\text{km}^2$ squares throughout England and Wales has been studied for the period 1930–1998 (Fig. 1). Six separate land use maps were available for these sites derived from a number of different surveys (Table 1). Each of the input maps were digitised, geo-corrected and thematically harmonised (Petit and Lambin, 2002) to enable comparison. A method to analyse the dynamics of change is presented which uses a number of derived spatial indices to capture key elements of the process, presenting them in combined form in a stability map. Such an approach builds upon similar work on change trajectories undertaken by authors such as Agger and Brandt (1988) who describe a 'lability index', Käyhkö and Skånes (2006) with a 'change index' and Crewes-Meyer's (2004) 'panel-metric' approach. However, the current study differs in that consideration is given to both the impact of different spatial scales on the resulting land use change metrics as well as an assessment of the impact of different temporal inputs on the final stability maps.

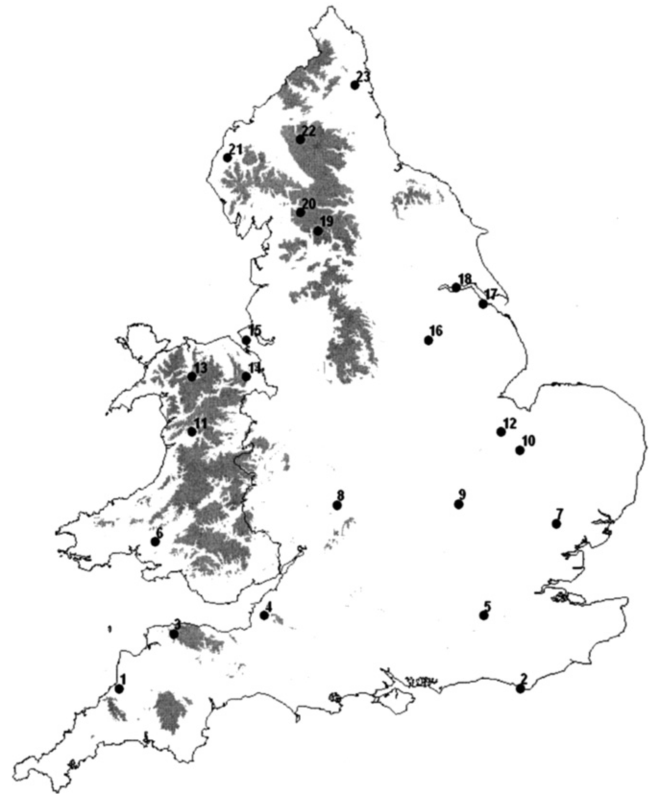

Fig. 1. The distribution of the 23 sample sites throughout England and Wales.

Using this unique time-line of land use change data three questions were asked about the study sites:

Table 1
The six land use maps used in the construction of the stability maps

Land use dataset	Dates	Notes	Reference
First Land Utilisation Survey	1930–1933	A national land use survey conducted at a scale of 6 in. to 1 mile or approximately 1:12,000	Stamp (1947, 1948)
Second Land Utilisation Survey	1960–1968	A national land use survey conducted at 1:25,000	Coleman (1961, 1977)
The Institute of Terrestrial Ecology (ITE) Survey	1978	A sample survey of selected 1 km^2 sites, conducted at 1:10,000	Bunce (1978)
The Second Institute of Terrestrial Ecology Survey	1984	A repeat of the 1978 survey which built upon and expanded the number of sites sampled. Again, the survey was conducted at 1:10,000	Barr et al. (1986)
Countryside Survey 1990	1990	An expanded repeat of the ITE Survey conducted at 1:10,000	Barr et al. (1993), Howard et al. (1996), Gillespie et al. (1996)
Countryside Survey 2000	1998	An expanded repeat of the ITE Survey conducted at 1:10,000	Firbank et al. (2003), Haines-Young et al. (2000), Sheail and Bunce (2003)

Note that the first two surveys produced synoptic, national maps whilst the other four were based on stratified random sampling. Sites surveyed in the 1978 ITE Survey were re-surveyed as part of the expanded surveys of 1984, 1990 and 1998.

1. Are there identifiable and systematic changes in this sample of rural landscapes in England and Wales over the study period 1930–1998?
2. Can specific trajectories of land use change be identified?
3. What impact does changing spatial and temporal resolution have on the stability metrics as calculated?

2. Methods

In order to answer these questions a method was devised which can be conveniently termed 'stability mapping'. This process systematically identifies those map-zones which have been most prone to land use change. As a method, it would be applicable to any location where detailed historical map data are available and will be illustrated here with sampled data from England and Wales.

2.1. Creation of the multi-attribute database

A GIS database was constructed which comprised 138 separate land use maps (6 (time-steps) × 23 (sites) = 138) with the constituent parcels of land coded into 1 of 20 basic land use categories (Table 2). These data were converted from polygons to a raster format with a cell size of 25 m^2 (5 m × 5 m) giving a grid of 40,000 cells per map. For each of the 23 sites the 6 land use grids were then combined into 1 multi-attribute grid which formed the input to the stability mapping process. The database files associated with these combined land use maps were then processed further to extract three derived spatial indices for each 25 m^2 cell, namely: similarity, turnover and diversity.

2.2. Derived indices

Similarity captures information about the dominance of any one class at a particular location throughout the time-span. So for example, if a cell recorded land use of: arable, grass, wood, grass, grass and finally arable, the similarity index would be 3. Turnover records how many changes occurred between adjacent pairs of years, so in the example given above the turnover value would be 4 whilst diversity is simply the number of different classes recorded for the six time-steps, which in this case would be 3.

These three indices were then combined using logical rules into one of six groups: stable, stepped, cyclical, dynamic, no constant trend (NCT) and (stable) (Table 3). Stable cells recorded exactly the same land use class in each of the time-steps. Stepped profiles indicate those locations where there had been one point of change between two land use classes, with stable land use either side of that point of change. In contrast, cyclical change is restricted to those areas where frequent change has occurred between just two categories. Dynamic change is defined as a high turnover between many different classes. In some locations, more than one of these four trends can be present showing that change has happened since 1930 but this change has been variable; these cells were classed as being of 'no constant trend'. Finally, there were some cells which showed a profile which was stable apart from one change—the decision was taken to class these cells as (stable) reflecting the dominant trend whilst still distinguishing them from those cells which were consistently one class. These six groups were then linked back to the GIS database in order to map the spatial trends at each site.

Table 2
The integrated land use classification used to link all six surveys

Code	Land use class	Total area of each land class across all 23 sites (2300 ha)					
		1930	1960	1978	1984	1990	1998
1	Arable	421.64	518.19	481.78	522.64	501.25	516.42
2	Grassland	1002.26	943.98	1050.52	941.50	947.04	1000.63
3	Water meadows	13.28	0.00	0.00	0.00	0.00	0.00
4	Chalk grassland	38.63	28.56	38.69	48.78	47.30	22.12
5	Coniferous woodland	17.60	32.68	61.71	44.42	57.30	51.09
3	Broadleaved woodland	119.15	113.04	104.55	133.09	129.44	162.32
7	Dense urban	7.17	55.73	61.31	67.88	75.81	69.61
8	Suburban	24.52	59.66	55.87	112.79	106.43	123.37
9	Agricultural buildings	4.18	4.45	4.87	7.33	7.76	8.55
10	Factories	0.00	0.60	0.00	0.00	4.69	2.67
11	Roads	43.18	43.51	46.35	39.76	41.32	38.76
12	Ports	0.00	0.00	0.00	0.00	0.00	0.00
13	Railways	14.46	17.45	11.56	9.85	9.60	8.37
14	Unproductive[a]	66.65	65.62	65.14	98.19	90.51	99.92
15	Gardens	15.71	0.83	0.00	0.00	0.00	0.00
16	Orchards	7.59	44.80	41.03	29.68	32.55	29.25
17	Still water	3.61	4.22	1.99	2.05	1.90	2.57
18	Running water	13.37	13.18	13.40	12.91	12.95	12.96
19	Heath and moor	422.18	288.68	196.49	164.39	169.27	86.66
20	Sea and estuary	64.77	64.76	64.77	64.77	64.77	64.77

This was based upon the original 1930s survey of Dudley Stamp. The following five surveys were more detailed and allowed the land use groups to be combined into the 20 categories shown here. Figures given show the combined area of each land use class across all 23 sites.

[a] The 'unproductive' category was initially defined by Dudley Stamp to include all land not involved in productive agriculture such as bogs, high moorland, saltmarsh and shingle. The terminology reflects the initial aims of the 1930 survey which focused on mapping the agricultural land of Britain.

Table 3
Combinations of the three spatial indices (similarity, turnover and diversity) in order to derive the six classes used on the stability maps

Turnover	Diversity	Similarity	Class	Example	Notes
0	1	6	Stable	AAAAAA	No changes
1	2	3, 4	Stepped	AABBBB	Only one recorded change between two dominant categories
1	2	5	(Stable)	ABBBBB	With a turnover of just 1, this pattern with two classes can only occur when the change is at the start or the very end of the time-line. This in its strictest sense represents a stepped change as above but it could also indicate a move towards stability
2	2	3, 4	NCT	ABBBAA	May show some evidence of cyclical change but the trend is not strong enough to warrant inclusion in that category
2	2	5	(Stable)	ABAAAA	With only one change this is classed as predominantly stable
2	3	2, 3, 4	NCT	ABBAAC	Exhibits elements of different trends
3	2	3, 4	Cyclical	ABBAAB	Cyclical change indicates possible management practices which favour rotation between two land use classes (mixed farming or forestry are two examples)
3	3, 4	2, 3, 4	NCT	ABCAAD	Exhibits elements of different trends
4	2	2, 3, 4	Cyclical	ABAABA	Rotational
4	3, 4, 5	2, 3, 4	Dynamic	CABBAC	Higher diversity
5	2	3	Cyclical	ABABAB	Frequent change between two categories—rotational processes dominating
5	3, 4, 5, 6	1, 2, 3	Dynamic	ABCABC	Frequent change between three or more categories which is associated with high turnover

2.3. Trajectories of change

Once the multi-attribute results grid had been created, each row of the associated data table recorded the area of all the trajectories of change found on each site. It was then a relatively simple task to identify the top 10 most common trajectories of change for each site. In order to reduce the potential dataset from 230 (23 sites × 10 trajectories) only those trajectories which covered more than 5% of the total area of any one site were included. This gave a dataset of 63 different land use change trajectories derived from 20 sites; 3 sites (6, 10 and 18) did not have any trajectories which met these size criteria. Once collated the data were sorted on the percentage area of the site which experienced such a trajectory of change and the most common trends were revealed.

2.4. Assessing the impact of spatial and temporal resolution

In order to test the spatial and temporal robustness of the measures previously described, a sensitivity analysis was carried out on the performance of these individual indices under different spatial and temporal resolutions. Four of the 23 sites were selected to test the impact of different data resolutions on the individual indices and the resulting stability map, 1 each from 4 representative landscapes commonly found throughout the UK, namely: lowland grassland (site 1), lowland arable (site 12), marginal upland (site 3) and true upland (site 21). The three indices were calculated from input data created at a resolution of 1, 5, 10, 25, 50 and 100 m for each of the four sites and the results compared.

Likewise the temporal stability of the indices was explored through a systematic removal of each of the 6 years from the time-line, recalculating the values adjusted to account for 5 years rather than 6 with the logical rules presented in Table 3 adjusted to account for the reduced inputs. An assessment could then be made of which input datasets appeared to be the most critical in defining the patterns recorded on the stability maps.

3. Results

3.1. The stability maps

Site 1 is a lowland grassland landscape in the south-west of England which has a mixture of stability classes reflecting a complex pattern of land use change and provides a good example of a stability map (Fig. 2). Although the majority of the area (61.1%) falls into one of the two stable classes the stability map shows how different patterns of change have been expressed over the landscape. Cyclical components (9.9%) are associated with agricultural fields on lower slopes and reflect a mixed farming profile which has included switches between arable crops (grown for livestock feed) and grassland. Such cyclical changes are confirmed when the diversity values are examined. Areas of high turnover on the middle map coincide with low diversity, indicating that the turnover is limited to two or three classes rather than a large number of different uses. The majority of change is expressed as either stepped change (9.9%) or of no clear trend (18%) and is concentrated in a band running from the north-west to the centre of the site. Stepped changes are more typically associated with the agricultural fields whilst the complex changes associated with the NCT areas coincide with steep valley sides and poor quality land which has been afforested since the 1950s.

Further examples of stability maps are given in Fig. 3 showing three different types of landscape: lowland mixed farming, lowland ‘urban fringe’ and remote marginal upland. Each stability map is shown with the associated 1:25,000 scale Ordnance Survey topographic map, to aid interpretation. As shown, it is rare for any part of the sample to be dominated by only one type of process, more typically different zones have followed different land use change trajectories and it is this information that the stability map summarises for the six time-steps.

When the area of the different groups is summarised across the whole sample, a number of trends were observed (Table 4). Stability is the dominant condition across the majority of the

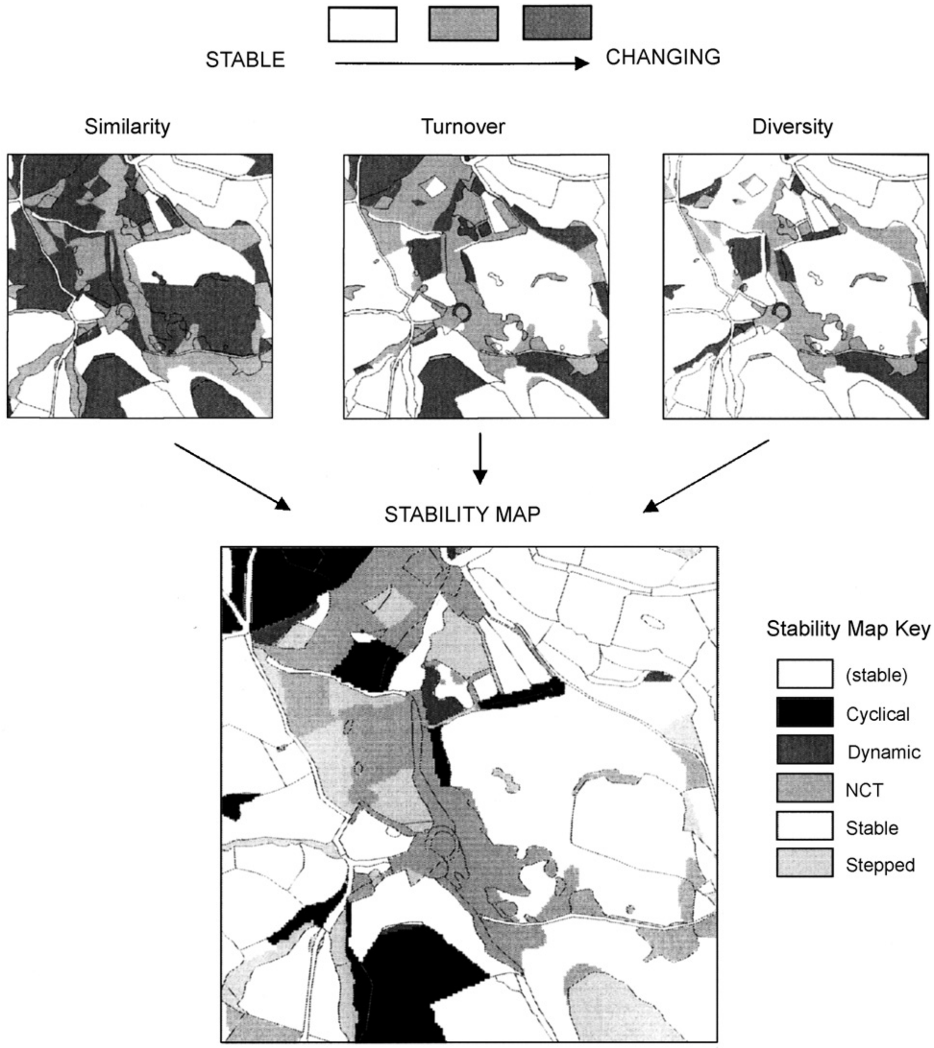

Fig. 2. The stability map for site 1 in south-west England shown with its associated inputs of similarity, turnover and diversity.

sites with on average 41% of the area of the sites recording no change across the 6 time slices, for 5 of the 23 sites this figure is more than 60%. If the figures in the (stable) column are also taken into account, the value would rise significantly for many of the sites, however, as described in Section 2.2, some of these figures relate to sites with only one change from the recorded sequence. Where this is at the start or the end of the sequence the process could equally reflect a stepped profile—this is an unavoidable limitation of the sample used and in some ways reflects the temporal edge effect.

Of particular interest is cyclical change which can only be identified where there are sufficient sample points to capture the variation. Overall, it is not common in the sample with only four sites having greater than 10% of their area identified as showing cyclical change, most notably, site 23 in north-east England with over 27%. Two others (site 11 at 14.94% and site 22 at 10.72%) have captured changes associated with long-term forestry. Both of these sites are situated on marginal or true upland and have significant areas of heavily managed conifer plantation. Again, the length of time that the sample covers (70 years) and the periodicity (six samples) has allowed such processes to be detected.

Dynamic change combines elements of high turnover with high diversity and is comparatively rare overall having been defined quite tightly to only include those areas where turnover was at least 4 and diversity at least 3. Two of the sites (16 and 19) did not have any zones which were classed as dynamic and another eight had values less than 1% of the total area. Only two sites (site 8 at 9% and site 11 at 6.97%) have an area greater than 5% of their total in this category. In general, such small areas of high turnover were associated with the fringes of settlements where patches of land adjacent to houses and farms were more frequently re-used between surveys.

These results do not mean however, that there was little change overall. The 'no clear trend' column also includes those areas which have experienced some turnover between different classes but not as frequently as the dynamic areas. It can be seen that on average more than 13% of the total area fell into this group. If values in the 'dynamic' and the 'NCT' column are added together, 14 of the 23 sites had more than 10% of their

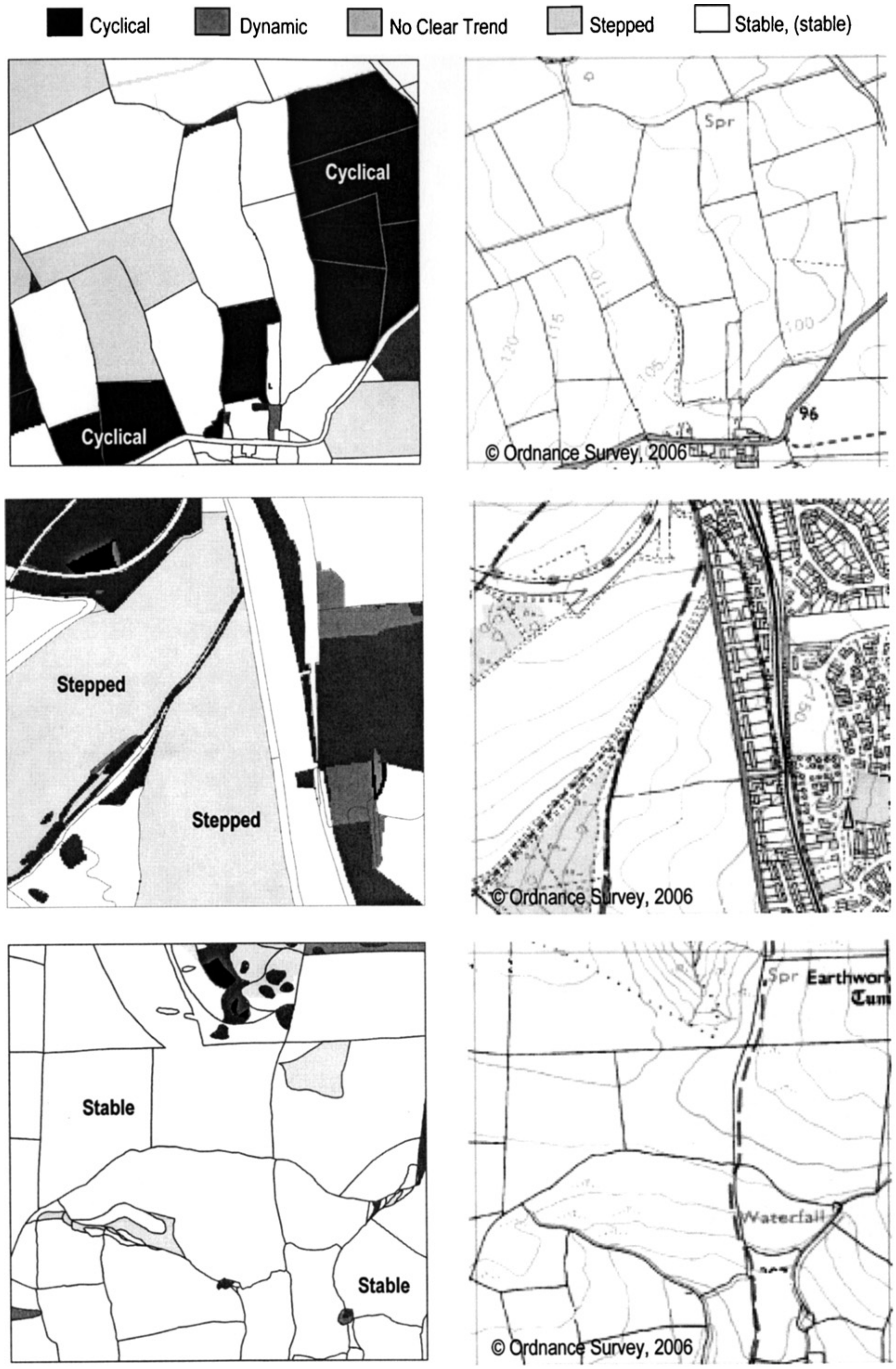

Fig. 3. Example stability maps shown for site 23 (a), site 5 (b) and site 3 (c) with the corresponding Ordnance Survey 1:25,000 map shown for orientation. Site 23 was a site where cyclical processes dominated being situated within a mixed farming landscape in north-east England. In contrast, site 5 was situated in the urban–rural fringe of London and was dominated by areas of farmland which had switched from more extensive grazing to fairly intensive arable at some point between 1930 and 1960. Site 3 was a stable site being grassland dominated in a marginal upland area.

total area in these changing categories with 6 of those more than 25% (sites 2, 5, 8, 9, 11 and 20). With over 55% of the total area falling into one of these two classes, site 8 was by far the most dynamic of all of the 23 sites. Here change was strongly associated with the area used for commercial orchards which had undergone initial expansion between 1930 and 1960, followed by periods of retraction during the later part of the time-line (Ilbery, 1985). Two of the other sites (5 and 9) included zones of the urban fringe and the dynamic components of both sites were associated with agricultural extensification of arable land in anticipation of housing development which was mapped from the 1978 survey onwards (Munton et al., 1988). The remaining two sites (11 and 20) were both upland sites where dynamic change was associated with the appearance of commercial

Table 4
The percentage cover of the six constituent stability classes as calculated for each of the 23 sample sites (each site = 100 ha.)

Site	Percentage cover of each class					
	Stable	(Stable)	Cyclical	Dynamic	NCT	Stepped
1	35.00	26.07	9.94	1.06	18.02	9.92
2	46.55	9.42	16.76	3.28	23.75	0.24
3	71.19	21.58	0.44	0.78	1.81	4.20
4	30.21	35.86	6.84	2.89	8.24	15.96
5	4.42	27.32	0.67	4.48	23.81	39.31
6	63.99	13.29	2.27	0.33	13.15	6.98
7	45.51	40.15	0.61	0.21	5.10	8.43
8	21.65	17.47	1.51	9.00	46.53	3.84
9	54.27	13.80	0.00	1.27	25.67	4.99
10	93.73	2.70	0.02	2.76	0.68	0.12
11	7.24	36.83	14.94	6.97	28.87	5.15
12	64.98	20.11	4.77	0.16	4.03	5.96
13	50.55	29.56	3.56	3.23	8.60	4.51
14	55.43	25.92	0.04	1.46	13.99	3.17
15	16.14	51.10	5.29	0.18	13.34	13.97
16	44.36	47.34	5.35	0.00	0.60	2.36
17	11.84	51.07	4.55	1.46	4.69	26.39
18	68.24	11.97	4.23	0.50	11.24	3.82
19	55.05	29.68	3.27	0.00	3.38	8.64
20	3.56	33.62	4.44	1.30	25.61	31.48
21	52.41	28.90	5.92	3.24	5.17	4.36
22	47.23	10.46	10.72	0.33	12.99	18.28
23	14.17	38.82	27.32	0.22	1.76	17.72
Minimum	3.56	2.70	0.00	0.00	0.60	0.12
Mean	41.64	27.09	5.80	1.96	13.09	10.42
Maximum	93.73	51.10	27.32	9.00	46.53	39.31

plantation forestry or with attempts to reclaim the moorland on the higher slopes of the valleys.

Finally Table 4 shows those areas of the sites which conform to a stepped land use change profile recording a clear change between one land use class and another. For three sites (5 at 39.31%, 17 at 26.39% and 20 at 31.48%) this stepped profile has been significant in their land use change profiles. It is typically associated with changing farm management—most notably the switch from grassland to arable, especially in the lowlands of England where mixed farming has become much less common since the 1970s (Bowler, 1982).

Each of the 23 separate stability maps represent useful output from which detailed case studies could be built by examining the results in conjunction with ancillary data including topographic maps, soil maps or derived data such as slope and aspect—all of which can aid interpretation. As an example of their use a summary analysis is presented which takes all 23 sites as input (equating to 2300 ha in total). The proportion of the area classified into the six stability groupings was compared against the most recently mapped land use from 1998 (Table 5). These results show that where values are higher than those given in the first row, that stability grouping is more common on that land use than might be expected by chance, and vice-versa for values which are lower. A number of key differences are highlighted in bold showing those values which vary by at least 10%.

Dynamic zones of the map are strongly associated with areas most recently mapped as woodland. This is initially somewhat surprising as woodlands, particularly broad-leaved ones are often longstanding features in a landscape and therefore it could be hypothesised that they would favour stable land use trajectories. What these results seem to be reflecting is the large overall increase in woodland throughout the sample sites as shown in Table 2 (broadleaved woodland increases from 119.15 to 162.32 ha between 1930 and 1998 with a similar increase in coniferous woodland from 17.60 to 51.09 ha over the same time period). Much of this newly afforested land would previously have been marginal land, especially in the uplands where poor quality grassland was converted (Mather, 1993; Tsouvalis, 2000). The dynamism can also be accounted for by managed conifer plantations, whose felling cycle would be significantly less than the 70 years of this study. Both grassland (0.22 versus 0.44) and built land use categories (0.01 versus 0.11) are significantly less dynamic that might be expected by chance. For the grassland category this reflects the amount of permanent pasture which is found in such farming regions. Once land has been developed either for housing or transport, it tends to remain as such for long periods of time, which explains the general levels of stability which are associated with it.

Cyclical change is more commonly associated with current arable land uses than might be expected by chance (0.36 versus 0.22) which fits with the concept of rotational change being implemented within the agricultural system. Also, in recent

Table 5
The relative proportions of each of the stability classes within seven land use groups as compared against the actual proportion of the land use groups observed in 1998 (values in italics)

	Land use group						
	Arable	Grass	Woodland	Built	Heath/moor	Water	Other
Actual proportions (1998 data)	*0.22*	*0.44*	*0.09*	*0.11*	*0.04*	*0.03*	*0.06*
Stable	0.29	0.43	0.06	0.06	0.06	0.08	0.03
(Stable)	0.31	0.43	0.07	0.13	0.02	0.00	0.03
Cyclical	**0.36**	0.44	0.06	0.06	0.02	0.00	0.05
Dynamic	0.23	**0.22**	**0.33**	**0.01**	0.01	0.00	0.08
NCT	0.14	0.37	**0.19**	0.04	0.04	0.00	0.03
Stepped	0.27	**0.32**	0.14	**0.00**	0.00	0.00	0.15

The seven land use groups were derived from the original 20 shown in Table 2 as follows: arable, class 1; grassland, classes 2–4; woodland, classes 5 and 6; built, classes 7–13; heath/moor, class 19; water, classes 17, 18 and 20; other, classes 14–16.

years, there has been a reappearance of small amounts of grassland in what were previously intensive arable landscapes. These take the form of small paddocks used for horse-grazing which are situated around the edges of existing settlements. As cereal prices continue to fall it has become more economic for the farmer to "grow horses" than to grow wheat. Cyclical patterns are emerging because many of these paddocks are on reinstated grassland that was ploughed up in the 1960s and 1970s as livestock were lost from the arable areas. Finally Table 5 shows that stepped land use change trajectories are much less commonly associated with current grassland areas than might be expected (0.32 versus 0.44) which implies that the grassland areas have tended to be long standing and relatively stable.

3.2. Trajectories of change

Trends in the most significant land use change trajectories for the 23 sites are summarised in Fig. 4 which shows the top 10 as defined by total area. Of these, six showed a stepped profile with the land use changing only once; the remaining four show a fluctuating profile. The top two involve a stepped change from grassland to arable and account for 160.8 ha in total. The third most common trajectory by area is an early switch from arable in 1930 to grassland from 1960 onwards. Three of the top 10 show stepped change from a semi-natural land use of moorland to grassland with 43.3 ha switching early (by 1960), 21.0 ha by 1978 and a much later switch occurring

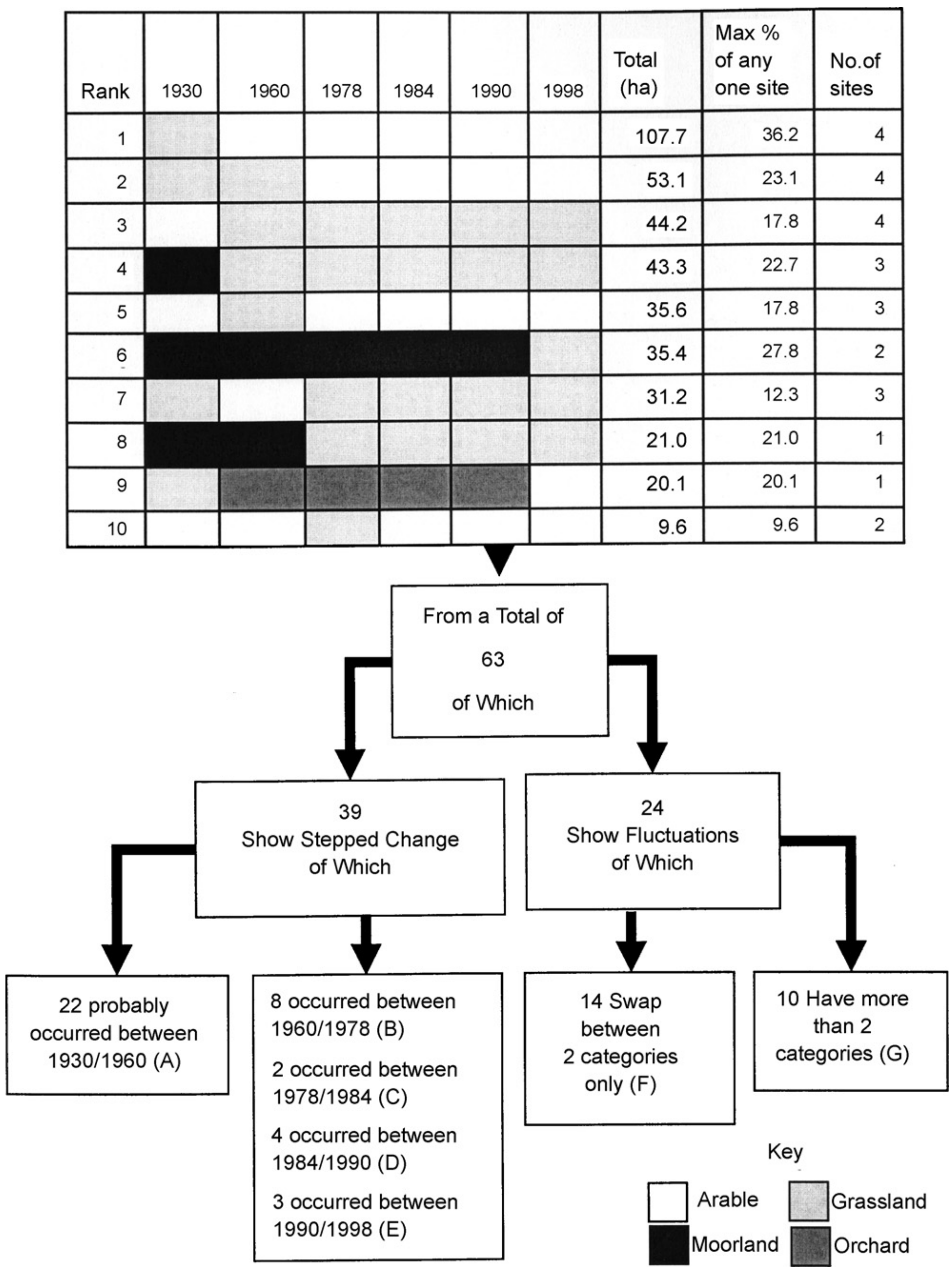

Fig. 4. A summary of the land use change trajectories for the 23 sample sites. The top half of the diagram shows the top 10 trends as defined by percentage area and includes combinations of arable, grassland, moorland and orchards. The breakdown of all 63 trajectories of change is given in the bottom half of the figure (see text for further details).

for 35.4 ha between 1990 and 1998. The remaining four trajectories show a more complicated pattern which fluctuates over time.

It can be seen from the lower half of Fig. 4 that different groups are discernible within these data (labelled A–G). Stepped changes are more common overall, with a strong dominance of early changes as shown by the value of 22 for group A, though it should also be noted that these trajectories would be classed as (stable) on the stability maps. Later stepped changes indicated by groups B–E are less common. Of the 24 trajectories which show some evidence of a fluctuating pattern (groups F and G), a subdivision is naturally made between those which swap between just 2 classes, of which there are 14 in total, and those which have more classes, with 10 examples. The former can be indicative of cyclical process as previously discussed. The latter is a more complex process which is often apparent near built land uses or can sometimes arise due to reclamation such as from moorland to grassland to conifer woodland.

3.3. The impact of varying spatial resolution

When tested, the stability groupings showed a high level of robustness to varying spatial resolution with differences only becoming apparent when shifting to much coarser grained inputs at the 50 and 100 m level. As would be expected it was the smaller areas of dynamic or cyclic change which tended to be smoothed out by the increased cell sizes. As cell size increased, rarer land use types tended to be lost from the input maps as the GIS algorithm used to convert from the vector maps to grids assigned the dominant land use value to the cell as a whole. The resolution that was chosen for the study (5 m) would appear to have been appropriate for the scale of the original mapping and served to capture the main characteristics of change in the landscape.

3.4. The impact of varying temporal inputs

It is apparent that across all four of the test sites the removal of the earliest dataset from 1930 has the most significant impact on the overall groupings found on the resulting stability maps (Fig. 5a–d). For three of the four sites this caused a large increase in the area of stable land indicating that land use has changed significantly early on in the time-span. For site 1 (Fig. 5a), these results are accounted for by reclamation of heathland which was brought into cultivation post 1930 and has remained managed grassland from this point on. This ‘switch’ is only evident if the early dataset is included in the analysis. A similar process has operated at site 3 (Fig. 5b) on the marginal upland site where moorland reclamation was carried out in the early part of the last century resulting in a switch to grassland. Site 12 (Fig. 5c) shows a similar pattern but reflects slightly different processes operating on this lowland arable site. Here the 1930s data record much greater areas of grassland, reflecting more mixed farming where livestock rearing remained important. As farming became more specialised, particularly on the favourable soils of the eastern parts of England, arable became very much more dominant and the grassland declined in significance (Allanson, 1996). Again

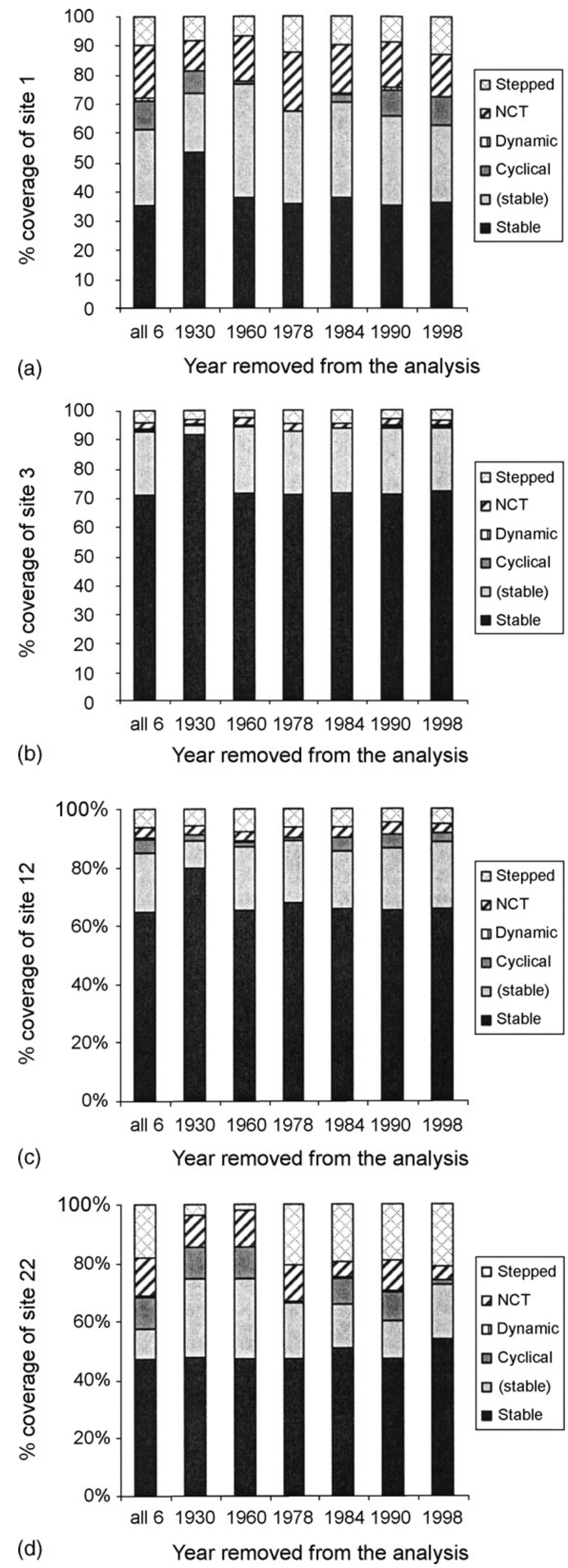

Fig. 5. The impact of changing temporal resolution on the resulting stability groups for site 1 (a), site 3 (b), site 12 (c) and site 22 (d) calculated at a spatial resolution of 5 m. The first column shows the distribution of the stability groupings across the site when all 6 survey years contribute to the calculation—this in essence represents the baseline situation. The following six columns show the impact of removing that particular year from the calculations.

the early dataset provides important historical context to the land use profile of this site.

Another significant change is brought about by the removal of the 1978 dataset from the sequence. This impacts most on the occurrence of cyclical components on the stability map and is most clearly seen on sites 1 (Fig. 5a) and 22 (Fig. 5d) where it disappears from the groupings. Clearly, with a fixed set of input datasets, capturing evidence for some of the more dynamic changes involving switches between land use classes is more open to chance. As we cannot go back and fill in any gaps in the time-line which appear to be too long, there is little that can be done. What can be said is that the greater the number of temporal samples the more likely it is that such patterns can be identified. As defined by the logical rules outlined in Table 3 a minimum of four datasets would be needed to detect cyclical change and five are recommended.

4. Discussion

Stability mapping has proved a useful approach to analyse land use changes in a sample of landscapes from England and Wales between 1930 and 1990. The method outlined provides a set of tools to help understand the processes operating to change land use patterns at particular sites and can be thought of as a form of exploratory spatial data analysis (Openshaw et al., 1987; Wu, 1999). Each of the component indices which create the stability map (similarity, turnover and diversity) is a useful spatial indicator, describing different facets of the land use change process. However, by combining these three measures through logical rules a new classification can be formed which allows differing sites to be compared in an objective, quantitative manner. Such indices and classifications are relatively simple to construct within a GIS and the results are intuitive, presented as they are on a map, but one which is based on a set of objective rules. It is necessary, however, to set these results in their proper context through the use of ancillary data and it is recommended that these should at least include topographic maps, agricultural and forestry statistics.

The three component indices (similarity, turnover and diversity) which are used to produce the stability map are correlated but each has something separate to offer in terms of map-based analysis whether it is a measure of stability or change. From a methodological point of view, diversity is the simplest to calculate, followed by similarity and then turnover. However, it is turnover which captures the most interesting information about the process of change and is therefore, perhaps the most valuable in constructing the stability map. Critically, each index can accommodate increased numbers of inputs and it does not matter how many extra datasets are added, the indices still condense the information into three single values from which the stability map can then be produced and compared across sites. The final product captures information about the process of change which cannot be fully explained when the three indices are considered separately.

Sensitivity analysis showed that the stability map is robust to variations in the scale of input data and that the resolution selected for this study was appropriate. For these sample landscapes, the results only began to vary significantly when the resolution of the input data was degraded to 50 m and above. Where possible, it is recommended that the chosen cell size should mirror the minimum mappable unit of the survey used as input. All of the six datasets used here were mapped at very similar scales of between 1:10,000 and 1:12,000 which gave further confidence in their suitability as inputs to such analysis.

Experiments conducted with the temporal framework confirmed the importance of having an appropriate number of inputs during times of significant socio-economic change. An understanding of the history of the landscape under study is useful in this respect. The timing of the First Land Utilisation Survey was particularly important in this study as it captured the rural landscapes of England and Wales during times of agricultural depression (Whetham, 1978; Brown, 1987; Martin, 2000) prior to the enormous changes that were instigated by the outbreak of the Second World War.

Post-war, technological innovations continued apace with large increases in productivity as the result of improved fertilisers and crop breeding (MAFF, 1968; Bowler, 1979). The Second Land Utilisation Survey of the early 1960s took place during this time and recorded significant changes in land use in both rural and urban Britain (Best and Champion, 1970). During the 1960s and early 1970s the rapid change in agriculture continued with a chemical and mechanical revolution taking firm hold across the rural landscapes of England and Wales (Robinson and Sutherland, 2002). By the time of the first ITE Survey in 1978, rapid changes to the appearance of rural landscapes had already been noted (Westmacott and Worthington, 1974). In addition, in 1973 the UK joined the European Economic Community (which later developed in to the European Union of today) and between 1973 and 1978 the rural economy of the UK underwent significant upheaval as the agricultural industry adjusted to the pricing structures of the Common Agricultural Policy (Winter, 1996). The timing of this third survey is particularly apt as it took place at the end of this period of adjustment and so hopefully captures the result of land use changes of this time.

From this point onwards the data become more regular and consistent in their availability and scope (1984, 1990 and 1998). In an ideal situation, an additional dataset immediately post-war (1945–1955) would have given the time-line even greater cohesion but none were available. The six datasets which were used provide a reasonable coverage of the time period under study and this is important in assessing the utility of the results.

As with any method based on historical archives a number of caveats to its use do apply. Firstly by transforming the vector information on the paper maps into a 25 m^2 raster an inevitable degradation of the source data occurs and some authors have cautioned against reliance on grid-based modelling (Fisher, 1997). However, it remains a practical approach to analyse large amounts of mapped data. Secondly, the method has only been tested on a sample of rural landscapes in England and Wales; its applicability to urban situations remains untested. Urban forms are complex and would almost certainly demand a more detailed set of input maps with a high degree of spatial co-registration. Thirdly, the metrics performed less well on unenclosed upland landscapes where real changes in land use may be outweighed by mapping errors introduced at the time of survey. That said, for the majority of the sites surveyed, the method worked well as land use parcels are clearly delineated by field boundaries, roads and waterways.

So what are the wider implications of such an approach and what does the method offer to researchers and the end-users of land use science? Planners represent a specific group of such users, concerned as they are with the apportionment of our land resource. For them, managing land use change remains a daily challenge and the prediction of future change inevitably involves the use of models built on theory or previous observation (Parker et al., 2003). Cellular automata (CA) provide an example of such a modelling approach with CA often built using just one or two land use datasets to formulate transition rules which in turn determine future states (Balzter et al., 1998; Weng, 2002; Wu and Martin, 2002). Such limited inputs are often questioned and the six datasets used in this case serve to highlight the true complexity of the process over time. Rather than a constant gradient of change which is unidirectional, the reality is that switches can occur rapidly in previously stable profiles and that cyclical processes can operate in certain locations. It is apparent from this result that past land use does not necessarily predict future change, therefore the assumptions underlying some models may need re-examining if their results are going to be realistic.

The stability map provides a spatial summary of systematic changes in land use at a detailed local level. Along with its inputs, it provides answers to the questions 'where', 'what' and 'how' land use has changed at known locations. Such an understanding is complementary to an examination of the non-spatial drivers of change (such as population increases, agricultural policy, world commodity prices) and provides a mechanism to link these sometimes abstract factors to a known landscape in order to see how such drivers may be expressed in change on the ground.

It has also been shown that large differences occur between varying types of landscape in different regions in England and Wales. Although the 23 sites used in this study were derived as a stratified random sample, specifically designed to capture as big a range of landscapes as possible, each one can be thought of as a regional case study. As such, the trends observed at each site may have more use as a predictive tool for land use change in that locality.

5. Conclusions

At the outset, three questions were posed concerning the nature of land use change at these sample sites. Firstly, are systematic changes in land use evident for the time period 1930–1998? The results have clearly highlighted a number of significant changes, with overall declines in low-input grassland (water meadows, chalk grasslands) and heathland/moorland. Over the same time period there have been significant increases in the areas of woodland, built land as well as in the area of marginal semi-natural land, mainly in the uplands where the maintenance of improved grassland on the fringes of the moorland is no longer economic in some places. What these summary statistics do conceal is the amount of dynamism within the sites, as parcels of land swap frequently between different land use categories. Typically, less than half of the 1 km^2 sites remained totally stable, though the trend did vary considerably on some sites.

Secondly, can common trajectories of change be identified? Within this sample, the most common trajectory of change was that from grassland to arable with an early switch occurring at some point between 1930 and 1960. Stepped trajectories were also more common than fluctuating trajectories incorporating more than two different land use types.

Thirdly, what impact does changing spatial and temporal resolution have on the performance of the indices and the resulting stability map? Tests showed that the indices were robust to changes in the resolution of the input datasets, only beyond 50 m (a 10-fold increase on the resolution actually used) does the stability map begin to alter significantly.

The stability mapping methodology outlined in this paper has shown that in long-settled agricultural landscapes such as those of England and Wales, the process of land use change is complex, multi-directional and not necessarily dependent on the preceding land use. Historical data are valuable in highlighting how frequently some rural landscapes may change over time. Rural views which may seem to the observer to be long-standing may actually be relatively recent when examined over a generation. Change can happen rapidly in response to socio-economic drivers which can be increasingly divorced from the geographic setting. Although looking backwards in time may not provide all the answers planners and scientists seek in terms of predicting future land use change, it is certainly a very good place to start to ensure that those predictions are at least plausible at the regional level.

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