PEER-REVIEWED ARTICLE

The Land Cover Map of Great Britain: An Automated Classification of Landsat Thematic Mapper Data

R.M. Fuller, G.B. Groom, and A.R. Jones

Abstract
The Land Cover Map of Great Britain was produced using supervised maximum-likelihood classifications of Landsat Thematic Mapper data. By combining summer and winter data, classification accuracies were substantially improved over single-date analyses. The map, based on a 25-m grid, records 25 cover types, consisting of sea and inland water, beaches and bare ground, developed and arable land, and 18 types of semi-natural vegetation. General cover is recorded at a field-by-field scale, while key landscape features, with strong spectral signatures, show patterns down to a minimum mappable unit of 0.125 ha. Comparisons with independent ground reference data showed correspondences which varied between 67 percent and 89 percent depending on the level of detail at which comparisons were made.

Introduction
There has been no complete land-cover map of Great Britain since the early 1960s (Coleman, 1961; Coleman and Maggs, 1965) and no published map since the 1930s (Stamp, 1962). None, until now, has been available in digital form. Thus, the process of land-use planning in Britain has been based, at best, on piecemeal surveys. The Land Cover Map of Great Britain was produced by the U.K. Institute of Terrestrial Ecology, in response to a wide and growing need for use of such data for environmental research and management.

Satellite images are valuable for mapping large areas, though the complexity of many managed European landscapes may demand data with a fine spatial resolution (Hill and Megier, 1988). The CORINE program on environment has set out to map all of the European Community, using visual interpretation and manual mapping methods to give minimum mappable units of 25 ha (CEC, 1992; Wyatt and Fuller, 1992). However, Britain's landscape is intensively used and the patterns of arable fields, pastures, settlements, and woodlands require a resolution of nearer 1 ha for accurate classification of the mixed terrain: only automated classifications could realistically offer this. Computer classifications have been made of the Netherlands (Thunnissen *et al.*, 1992), Finland (Kuittenen and Sucksdorff, 1987), and Sweden (Satellitbild, 1992). Regional land-cover statistics have been derived by classification of Landsat images (Hill and Megier, 1988).

Experiments with Landsat Thematic Mapper (TM) images in Britain (Jones *et al.*, 1988; Fuller *et al.*, 1989a; Fuller *et al.*, 1989b; Jones and Wyatt, 1989; Fuller and Parsell, 1990) gave information on major cover at field-by-field scale (i.e., *circa* 1 ha). The use of composite, summer and winter, data improved the detail and accuracy available (Fuller and Parsell, 1990) to operational status (Fuller *et al.*, 1989b; Wickland, 1991; Townshend, 1992). At that time, an independent, field-based, sample survey of Britain was planned (Barr, 1990). The field survey and a Landsat-based classification were brought together under the "Countryside Survey 1990" (CS90) project (Bunce *et al.*, 1992).

Objectives
This paper records details of image availability, the land-cover classes, methods used for classification, and techniques used for post-classification corrections. It describes the results in terms of maps and output data, and assesses the quality against independent field surveys. It outlines areas for future developments of remote sensing for land-cover mapping in Great Britain.

Methods

Landsat TM Image Acquisition
Landsat TM data were used because, unlike the alternatives, the sensor includes a detector which is sensitive to middle infrared (IR) wavelengths (TM band-5, 1550 to 1750 nm), important in separating a wide range of vegetation cover-types (Townshend *et al.*, 1983). The baseline date for the mapping was 1990 but, to accommodate any image shortages, e.g., due to cloud cover (Legg, 1991), ± 2 years were allowed. Combined summer and winter data helped to separate arable areas, seasonally bare, from permanent, semi-natural, vegetation; deciduous trees and grasslands were differentiated from evergreen examples; urban areas and bare ground were characterized by their bare appearance all year (Fuller and Parsell, 1990). The ideal "summer" period covered the main plant growing season, mid-May to late July. "Winter" covered the time from the first frosts (*c.* mid-October) to early

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spring (*c.* mid-March). In practice, the useful periods shifted with altitude, latitude, and the year in question. The final choice was compromised by image availability, and six weeks either side of ideal dates was sometimes needed to complete local cover. Eight Landsat paths cover Britain, and 46 different scenes were required for this study. Summer-winter composite images were used whenever possible. Where this proved impossible, single-date cover was used.

Geometric Correction and Image Registration

All analyses were made on International Imaging Systems (I²S) Model 75 and IVAS image processors using System 600 software. TM summer data were geometrically registered to the British National Grid (BNG) using control points on 1:50,000-scale Ordnance Survey maps. The image was then transformed to fit a polynomial model (Schowengerdt, 1983) using cubic convolution resampling to give 25-m output pixels. The winter data were then resampled to fit control points identified on the corrected summer scene. The summer/winter composite images were registered to give a single output image. This image contained six bands of data, three each from the original summer and winter scenes, namely Landsat TM bands 3, 4, and 5, i.e., red, near, and middle IR (Fuller *et al.*, 1989a; Fuller *et al.*, 1989b; Fuller and Parsell, 1990). These bands were chosen for their characteristic responses from vegetation (red for chlorophyll absorption and IR for mesophyll reflections). They were also less affected by haze problems than was the blue-green part of the spectrum. Alternative band combinations and transformations were tried but rejected in pilot studies (Fuller and Parsell, 1990).

Maximum-Likelihood Classification

An appropriate land-cover classification system was the key to a consistent, accurate, and useful cover map. By reference to other surveys, it was possible to draw on a wide range of experience in vegetation mapping, and to devise a system (Table 1) suitable for multiple uses. The classification used a Bayesian maximum-likelihood classifier (Schowengerdt, 1983) implemented in the I²S Model 75 hardware (Settle and Briggs, 1986).

Training areas were based on knowledge derived from field reconnaissance surveys. Reconnaissance routes were planned to encompass as much landscape diversity as possible. Images of the route were photographed and printed at around 1:60,000 scale. Details of land cover were marked onto the photographs, while following the route in a vehicle, recording wherever uniform land parcels were seen in the field and identified on the hard copy image. Frequent stops were made to examine species details and any other factors which might affect the exact classification of an area. Typically, field reconnaissance identified the cover in about 1200 land/water parcels per Landsat scene, some 30,000 throughout Britain.

A sample of the reconnaissance information was chosen for training the classifier, interactively outlining the largest and most uniform examples. Transient features such as specific annual crops were not of immediate interest, so wheat and barley, for example, were treated as spectral subclasses of arable land. Most cover types required subdivision into a number of spectral subclasses (Kershaw and Fuller, 1992). For example, in undulating terrain, most cover types showed strongly sunlit and shaded variants. Typically, 70 to 80 spectral subclasses per scene were defined in training and later aggregated to give the 25 target cover classes. As far as possible, there were five or more training areas per subclass, with a grand total of 100 to 200 pixels, but a minimum of 30 pixels was allowed where training areas were small or few in number (Kershaw and Fuller, 1992).

TABLE 1. THE LAND-COVER CLASSIFICATION TO 25 "TARGET" COVER TYPES.

Suburban/rural development	Bracken
Urban development	Rough pasture/grass heath
Sea/estuary	Grass moor
Inland water	Lowland bog (herbaceous)
Beach/mudflats/cliffs	Upland bog (herbaceous)
Saltmarsh/intertidal vegetation	Open shrub heath
Inland bare ground	Open shrub moor
Tilled land (arable crops)	Dense shrub heath
Mown turf/grazed pasture	Dense shrub moor
Meadow/verge	Scrub/orchard
Rough/marsh grass	Deciduous/mixed woodland
Ruderal weed	Coniferous/evergreen woodland
Felled forest	

The classification process extrapolated from these training data to identify all other pixels in the scene with statistically similar spectral characteristics. By defining a rejection threshold (Kershaw and Fuller, 1992), it was possible to reject only those odd pixels which were dissimilar to all of the training data and thereby to classify about 98 percent of the scene. The process of training and classification was an iterative one. It involved preliminary classification, inspection of results, comparisons with reconnaissance data, editing or addition of training subclasses, then reclassification, through several cycles before completion of a final cover map for each scene.

Post-Classification Refinement

Cloud, Cloud-Shadow, and Snow Masks

Where cloud cover was extensive, erroneous classifications were interactively cut out and substituted with cover data based on a single date. Where cloud cover was more dissected, it was necessary to use automated procedures. Masks of cloud were made by defining a brightness threshold on TM band 3 (red), above which the cover was taken to be cloud. To avoid problems with haze around cloud-fringes, the mask was grown by six to ten pixels (in practice, by two pixels at one-third or one-fifth scale before restoration to full size), depending on the extent of haze. To remove cloud shadow, a low brightness threshold sometimes successfully defined a shadow mask; if not, a suitably displaced version of the cloud mask was added to the original. The completed cloud-plus-shadow mask was then used to cut holes in the erroneous multitemporal data and to select patches from a classification based upon the one good date. Snow masks were also needed in some winter scenes; again, these were based on brightness thresholds in band 3 (red), and the resulting masks were used to select data from the summer-only land cover.

Coastal Masking

Beaches were often confused with urban areas. Sea and inland water bodies often had identical spectral signatures. Saltmarshes were sometimes confused with arable crops. By delineating the coastline, it was possible to correct "maritime" habitats on land and "terrestrial" habitats at sea. A coastal mask was made semi-automatically on the image processor: the cover map was sampled to one-third scale and classes were aggregated into maritime and terrestrial types. A 5- by 5-pixel majority filter was used to remove small pockets of "terrestrial habitat" at sea and *vice versa*. The mask was then enlarged back to full size. Pockets of less than 7 ha were thus removed. Minor misregistrations around the coastline, and any larger pockets of error which remained, were removed interactively. By overlaying the mask onto the original map, it was possible to identify and automatically correct terrestrial-maritime confusions.

Upland Masking
The separation of upland and lowland cover types was often made difficult by the similarities in dominant plant species present, e.g., heather on both heaths and moors. Other floral differences, combined with phenological, topographical, and soil differences, allowed upland and lowland habitats to be separated with about 70 percent success. Small pockets of misclassified lowland habitat, in an extensive upland area (and *vice versa*), were filtered using procedures similar to those used for coastal masking.

Urban/Suburban Masking
The complex mosaics of vegetation and built-up land in urban areas were sometimes misregistered between summer and winter images, which gave pixels the same characteristic as arable land, namely, a bare appearance on one date, vegetated on the other; where deciduous trees overhung tarmac and concrete, the same arose. These led to some patches of vegetation in urban areas being misclassified as arable land. An urban mask, made by filtering an aggregated urban/suburban class at one-third scale, was used to correct "arable" areas under the mask. Trees, water bodies, and grasslands were allowed to remain, being normal features of urban environments.

Post-Classification Filtering
To simplify the data, various filtering procedures were considered. It was concluded that the majority of pixels showed the real complexity in the landscape rather than "noise." Thus, two or more pixels of a subclass usually denoted the real presence of a feature. However, single isolated pixels were probably erroneously classified. Therefore, isolated pixels of a subclass were removed from a 3- by 3-kernel filter.

Building the Mosaic of Great Britain Land Cover
The mosaic of full land cover was built employing an intermediate stage, which stored the data as BNG 100-km squares. As classification of a scene was completed, the sections were cut and stored in their 100-km square. As new overlapping scenes contributed data to the same square, edges were matched within the overlap zone by interactively defining a sinuous blend line, along uniform features, common in classification on both scenes. Where quality differences existed, the blend line maximized the use of the better data. Building the full mosaic of Britain involved butt-joining the completed 100-km squares.

Comparisons with Reference Data
Countryside Survey 1990 — The Stratified Sample of 1-Km Squares
A field survey was based on a 32-class environmental stratification of BNG 1-km squares: full details are given by Howard and Barr (1991). In 1990, field surveyors visited each of 508 sample 1-km squares, recording, among other details, ground cover, plant species dominance, and land use. The spatial details were recorded on Ordnance Survey 1:10,000-scale maps supplemented with airphoto-interpreted vegetation outlines. The maps were digitized within an ARC/INFO GIS to form vector-digital files for each 1-km square. Vector data were converted to raster for 143 squares (a minimum of four per stratum). Field classes were aggregated to give cover types corresponding, as far as possible, to those used in Landsat mapping. The data were compared, pixel-by-pixel, with the Land Cover Map, examining correspondences for all pixels and then separately for within-field pixels, i.e., excluding pixels falling across vector field boundaries.

Maps of Moorland and Heathland 10- by 10-Km Squares
The Land Cover Map was compared with four 10- by 10-km moorland areas in northern England. The test areas were surveyed independently by a field botanist who recorded moorland cover onto Ordnance Survey 1:25,000-scale maps using definitions based on species contents, management, and enclosure. The equivalent sections of the Land Cover Map were plotted onto Ordnance Survey 1:25,000-scale map sheets. Comparisons were made by scoring the field maps and the Landsat maps using a grid of points. A 10- by 10-km area of farmed heathland in eastern England was mapped by air photo-interpretation (API) of 70-mm, 1:10,000-scale photographs made in 1987. Field checks against ground data showed the API to be 94 percent correct. The 11 original Landsat cover types present in the area were simplified to a list of nine aggregate classes to compare with the API. By projecting the Landsat maps (in slide form) onto the API maps, direct comparisons were made for each land parcel.

Results and Discussion

Map Production
In all, 88 percent of Britain was classified from combined summer-winter images, and 12 percent from single-date, mostly summer, data. Just 0.4 percent of Britain was obscured by cloud cover on both summer and winter images. Another 2 percent which was unclassified represents unusual, hence unidentified, cover types. The missing areas of offshore islands represent just 0.1 percent of Britain. Plate 1 shows the full map of Great Britain, though much generalized for reproduction at this small size. At full resolution, Plate 2 (London) and Plate 3 (the North York Moors) illustrate the detail which has been mapped throughout Britain. Townshend (1983) calculated that the minimum accurately mappable unit from TM data would be on the order of 3 to 5 ha. In practice, most features of 1 ha show clearly, giving a map which shows patterns at a field-by-field scale. Superimposed on this "minimum accurately mappable area" is a finer pattern of those smaller features with strong enough spectral signatures to discriminate them from the background cover; for example, roads, farms, shelter belts, water bodies, and grass tracks are evident throughout the cover maps. After removal of isolated pixels, the Map shows units down to two pixels (0.125 ha).

The cover classification system was applicable to all the significant cover types encountered in the survey. Their definition had been based on a consultative exercise, backed by a wealth of experience in such mapping, because, in practice, the cover of Britain has been widely mapped, but in a piecemeal way. The Land Cover Map proved the feasibility of mapping these on a collective basis. The masking procedures have provided simple, innovative approaches for refining the classification. Filtering procedures, which only removed isolated pixels, avoided loss of real detail.

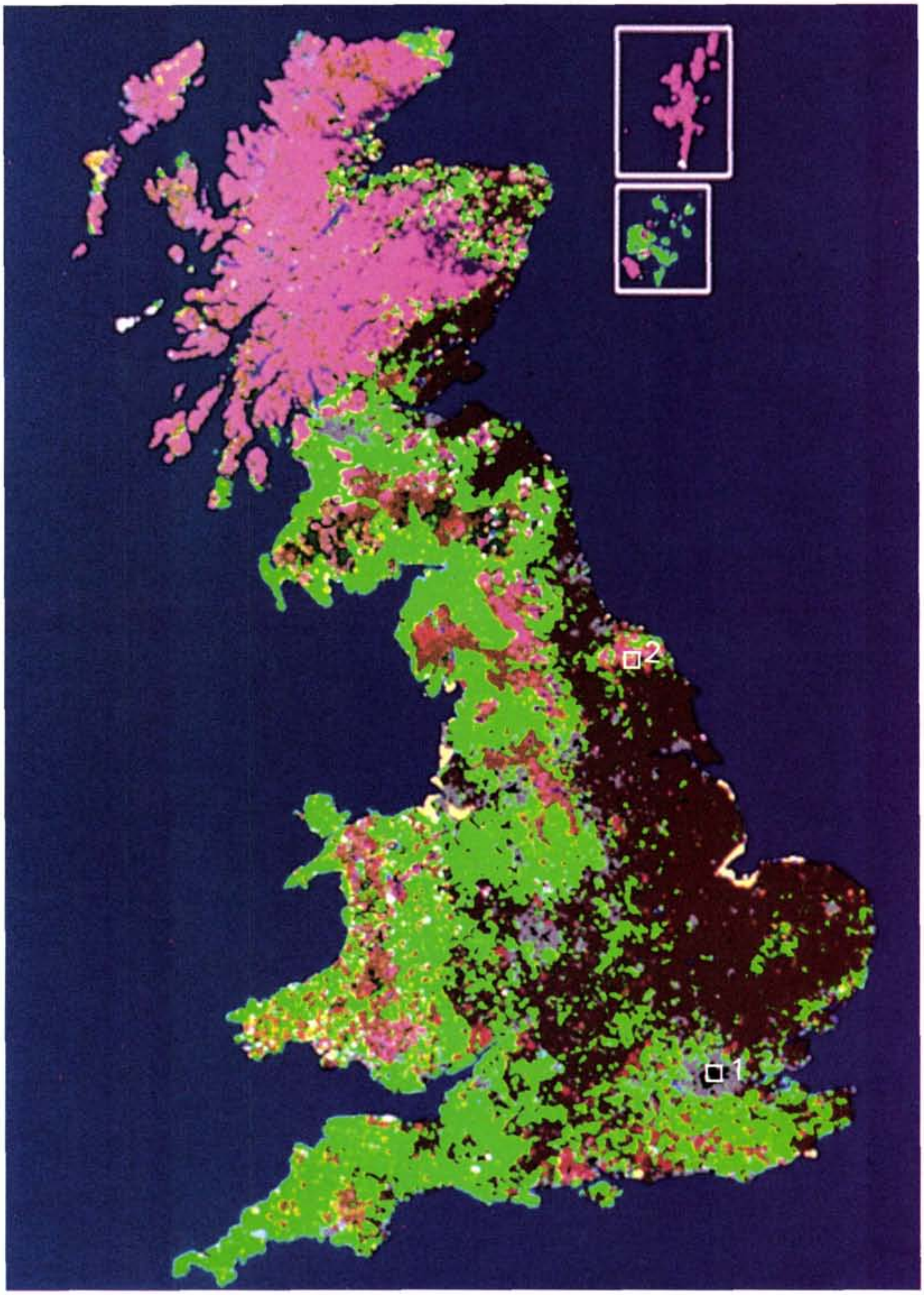

Plate 1. The Land Cover Map of Great Britain - an overview. The predominant colours are: blue - sea and inland water; cream - beach/mudflat/cliffs; black - urban development; grey - suburban/rural development; brown - tilled land; mid green - meadows/pastures/amenity grass; yellow - rough grazing/grass moor; pink - grass/shrub heath; purple - shrub heath; dark green - coniferous woodland; red - deciduous/mixed woodland. The two sites shown at full resolution in Plates 2 and 3 are located on this Plate and labeled with numbers 1 and 2, respectively.

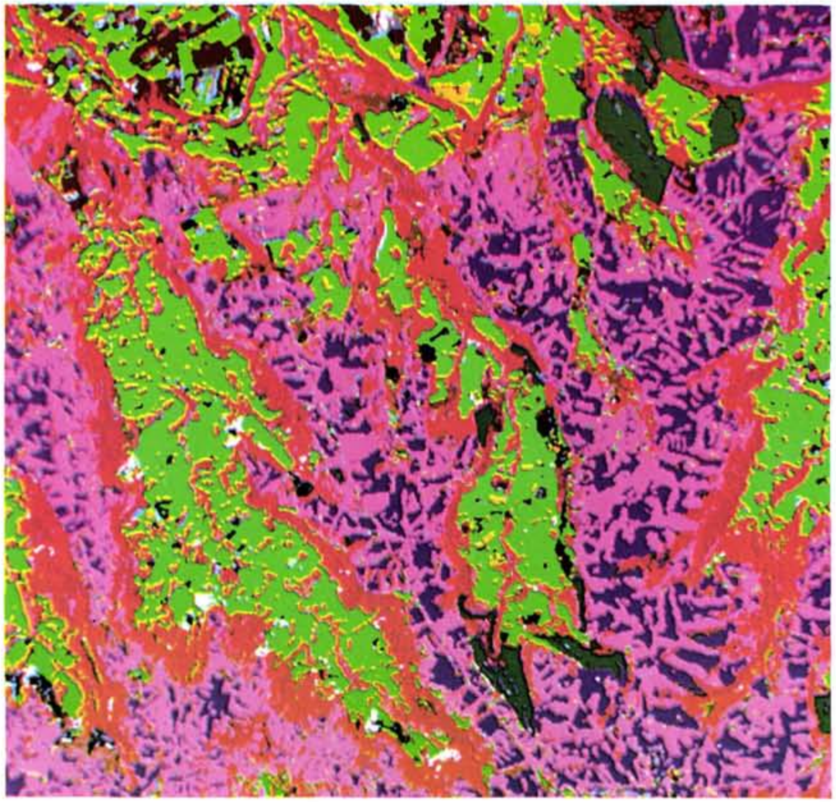

Plate 2. A 12.8- by 12.8-km section of the land-cover map for central London. It is possible to see the urban center (black) giving way to suburban areas (grey) and the grass areas (green) of the London Parks such as Hyde Park (top left) with water bodies (blue); note the fine detail, e.g., the "herring-bone" pattern of suburban streets or the bridges (grey) across the River Thames.

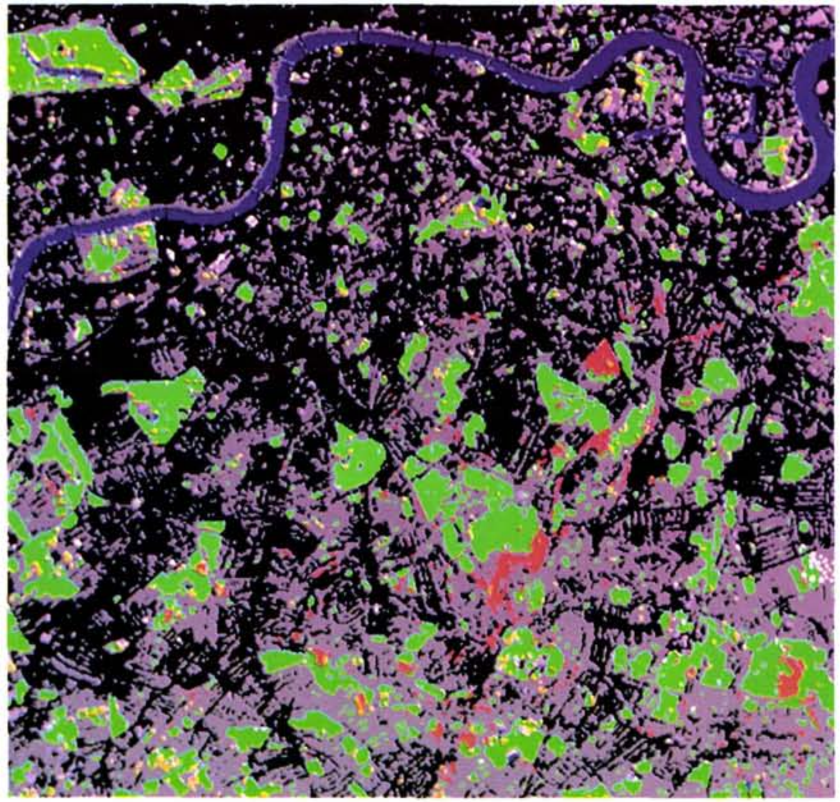

Plate 3. A 12.8- by 12.8-km section of the land-cover map for the North York Moors: this shows the heather moorlands (purple), with the regular patterns of burnt moorland (pink) comprising mixed grass and the regenerating heather (so managed for grouse). Note the valley sides with bracken (orange), steeply dropping down to the valley floor of pastures and meadows (green).

TABLE 2. CORRESPONDENCE, AS INTEGER PERCENT, BETWEEN FIELD AND LANDSAT SURVEYS, MEASURED ON A 25-M RASTER, IN 143 1-KM SQUARES: RESULTS INCLUDE WITHIN-FIELD AND BOUNDARY PIXELS. COLUMN NAMES ARE ABBREVIATED VERSIONS OF ROW NAMES.

Field/Landsat	uncl	subn	sea	water	coast	sm	bare	tilled	man/g	rough	brkn	h.m.g.	bogs	oshrub	dshrub	decid	conif	Total %
Unclassified																		1
Suburban/urban		3						2	2									8
Sea/estuary			2															2
Inland water				1														2
Coastal bare			1		1													3
Saltmarsh																		0
Inland bare																		1
Tilled land	1	1						14	3									21
Managed grass	1							3	18	1		2		2		1		29
Rough/marsh grass									1									2
Bracken																		1
Heath/moor grass												2		2				6
Bog												2	1	5	1			10
Open shrub												1		2	1			5
Dense shrub																		1
Deciduous/mixed								1	1							2		6
Coniferous														1		1	1	4
Field-surveyed	3	5	3	1	2	0	1	21	27	2	2	9	3	13	3	4	2	100

direct correspondence (sum of diagonal)	46
correspondence allowing for differences in cover-interpretation between surveys	67
correspondence allowing for differences in cover-interpretation and changes in time between surveys	76

Apparent discrepancies in row and column totals are due to integer rounding

Correspondence with Reference Data

Quality checks require access to "ground truth data," but the accuracy of such data is rarely known (Congalton, 1991). Conventional maps are most commonly used, but their division of a continuum of landscape patterns into discrete classes, with hard boundaries, is not "truth" but an artificial generalization which achieves different results according to the rules and methods employed. A recent study has revealed the wide variations in definitions of land cover (Wyatt *et al.*, 1993). In assessing the Land Cover Map, it is important to note that the reference surveys also set out with different methods, different objectives, and also differing potential in terms of the details they could record. Comparisons can only give indications as to Land Cover Map accuracy, but they help point to sources of error and highlight the impacts of generalization and class definition.

Countryside Survey 1990 — The Stratified Sample of 1-Km Squares

Registration of the Landsat-derived raster maps to 143 vector field maps of 1-km squares showed average displacement to be 0.8 pixels (20 m): 75 out of 143 squares needed no shift to achieve correspondence with vector overlays, 43 squares needed a one-pixel shift, 15 squares needed two pixels movement, and only ten squares needed more than two pixels movement relative to the vectors. This positional error is fully acceptable for most applications of the data. However, misregistrations, though minor, have undoubtedly increased the number of mixed pixels in summer-winter composite images and caused errors in classifications. Comparisons between the 146 field and Landsat 1-km squares gave correspondences, including boundary pixels (Table 2), and then excluding pixels falling across vector boundaries (Table 3). Direct correspondence is 46 percent.

Many of the apparent discrepancies are due to significant differences in class definitions. Whereas the Landsat classification, like the Ordnance Survey, used a hydrological definition of bogs, the field survey used a botanical definition which, in contrast, included wet moorlands. There were also differences in how the two surveys divided the continuum from grass, through heather-grass mixtures, to dense shrub heaths. There were differences, too, in dividing the continuum from rough grasslands to managed swards. There are no fixed conventions in such divisions, and variations can arise between individual surveyors within a survey. A quality assurance exercise, which re-examined the 1-km field data, showed an average 84 percent correspondence when the original surveyors' coding of land cover was compared with a quality standard.

The various differences in definitions show themselves as departures from the diagonal line in the correspondence matrices (Tables 2 and 3). However, because the tables are arranged so that similar classes lie next to each other, the diagonal trend is still clearly evident. The differences cannot be thought of as errors either way, but rather as differences in interpretation, where neither survey is more "correct." Some differences show up as clear departures from the diagonal. For example, managed grasslands within urban/suburban areas were ignored by the field survey, which treated urban zones as uniform and continuous. Allowing for different definitions, the overall correspondence is 67 percent.

The biggest component of map error is probably the misclassification of mixed boundary pixels. Some 40 percent of all pixels adjoin or cross a vector boundary and were thus made up of mixed cover types and additional boundary features. Correspondence was raised to 71 percent when boundary pixels were excluded. There are minor discrepancies due

TABLE 3. CORRESPONDENCE, AS INTEGER PERCENT, BETWEEN FIELD AND LANDSAT SURVEYS, MEASURED ON A 25-M RASTER, IN 143 1-KM SQUARES: RESULTS EXCLUDE PIXELS LYING UNDER VECTOR BOUNDARY. COLUMN NAMES ARE ABBREVIATED VERSIONS OF ROW NAMES.

Field/Landsat	uncl	subn	sea	water	coast	sm	bare	tilled	man/g	rough	brkn	h.m.g.	bogs	oshrub	dshrub	decid	conif	Total %
Unclassified																		1
Suburban/urban		3						1	1									6
Sea/estuary			2															3
Inland water				1														2
Coastal bare			2		1													3
Saltmarsh																		0
Inland bare																		1
Tilled land	1	1						19	3	1								27
Managed grass	1							3	21	1		2		1		1		31
Rough/marsh grass									1									1
Bracken																		1
Heath/moor grass												2		1				5
Bog												2	1	4	1			9
Open shrub														2	1			4
Dense shrub																		0
Deciduous/mixed									1							1		4
Coniferous														1		1	1	4
Field-surveyed	3	5	4	2	1	0	1	24	28	2	1	8	2	12	3	4	2	100

direct correspondence (sum of diagonal)	52
correspondence allowing for differences in cover-interpretation between surveys	71
correspondence allowing for differences in cover-interpretation and changes in time between surveys	76

N.B. apparent discrepancies in row and column totals are due to integer rounding

to geometry, where a feature was correctly classified but slightly displaced. In dissected landscapes, this would have had a major impact. It is desirable, though not easy, to distinguish between misclassification and misregistration. The satellite-derived map might be an accurate measure of cover, pattern, and relative distribution, but with minor spatial differences relative to equivalent products.

Other differences reflect changes in cover between surveys, sometimes two years apart. For example, a pasture on one date that was ploughed on the other. If we allow for likely time-based changes, overall correspondence is measured at 76 percent including boundary pixels, or 82 percent excluding boundaries.

TABLE 4. LAND COVER (SQUARE KILOMETRES) FOR 17 CLASSES, IN ENGLAND, SCOTLAND, WALES, AND FOR ALL OF GREAT BRITAIN (GB).

	England	Scotland	Wales	GB
Unclassified	2,157	1,454	1,065	4,676
Suburban/urban	13,802	1,437	696	15,935
Sea/estuary	2,943	6,079	631	9,653
Inland water	406	1,245	71	1,722
Coastal bare	644	546	142	1,332
Saltmarsh	277	52	44	373
Inland bare	1,010	1,388	154	2,552
Tilled land	43,312	6,878	1,095	51,285
Managed grass	44,426	12,918	8,230	65,574
Rough/marsh grass	1,981	1,638	666	4,285
Bracken	1,281	1,159	1,173	3,613
Heath/moor grass	7,598	10,681	1,938	20,217
Bog	277	3,779	233	4,289
Open shrub	2,342	23,822	1,502	27,666
Dense shrub	1,232	5,378	577	7,187
Deciduous/mixed	7,794	1,918	2,534	12,246
Coniferous	2,199	4,668	883	7,750
Grand total	133,681	85,040	21,634	240,355
Terrestrial area	129,817	78,363	20,817	228,997
Land area	129,411	77,118	20,746	227,275

Maps of Moorland and Heathland 10- by 10-Km Squares

The comparisons between 1:25,000-scale ground-based maps of moorlands and the Land Cover Map equivalent areas show that there was an 89 percent agreement in mapping moorland and non-moorland areas. Correspondences between the API of heathland and Landsat equivalent areas was measured at 78 percent. Assuming that the airphoto-map's 6 percent error would not directly coincide with independent errors in the Landsat product, this would suggest a Landsat map accuracy of nearer 83 percent. If differences in grassland were removed, overall agreement was raised to 88 percent for a comparison between arable, grass, broadleaf, evergreen, heather, and built-up cover-types.

Land Cover in Britain

Table 4 gives land-cover statistics for an aggregated list of 17 key cover types in Britain. The total land area, 227 275 km², is within 178 km² of the 227 453 km² quoted by Whitaker's Almanac (Anon., 1992). The difference (0.1 percent) is negligible and may partly relate to tidal conditions, and also to the small missing sections of offshore islands. In England, the predominance of tilled land and managed grass is notable with each covering 34 percent of the surface. Suburban and urban land in England amounts to 11 percent, a much higher proportion than in Scotland or Wales. Woodlands cover 8 percent and heath/moorland/bog categories add to make 9 percent. Semi-natural vegetation (including managed grasslands) covers about half of England. In Scotland, the much higher cover of heath/moor/bog at 57 percent was to be expected, with managed grasslands also important at 17 percent; tilled land covers just 9 percent of Scotland and urban areas amount to only 2 percent. Established coniferous forests now cover 4 percent of Scotland. Semi-natural vegetation, including managed grasslands, covers over 80 percent of Scotland. In Wales, managed grasslands dominate with 40 percent cover; tilled land covers just 10 percent. Woodlands are important with 16 percent cover and heath/moor/bog areas form 20 percent of the country. Suburban/urban areas only occupy 3 percent of the country while semi-natural vegetation covers more than 80 percent of Wales.

Applications of the Land Cover Map

Applications are the true mark of success of the Land Cover Map. The data have already found some 70 users in areas of policy and planning, landscape and wildlife management, environmental chemistry, management of natural resources, and environmental impact assessments. There are existing users in the government departments, government agencies, the utilities, industry, commerce, and the various consultancies working for all such organizations. Uses include applications which integrate land cover with topographic and thematic data in GIS for inventory, for predicting changes, to help devise management prescriptions, and to monitor successes and failures of policy decisions.

Conclusions

Effectiveness of Mapping Procedures

The Land Cover Map of Great Britain has been made by a semi-automated classification of TM data. The map gives a field-by-field scale of detail, with patterns recorded on a 25-m grid. The information is available in digital form, so facilitating access to the map information and assisting manipulation in applications of the data.

The methods for mapping the land cover worked the length and breadth of Britain. This included terrain from sea level to the highest peaks (1300 m), in a diverse and finely dissected landscape ranging in variety from urban London, through arable eastern Britain, to semi-natural communities including coastal habitats, grasslands, wetlands, heaths, moorlands, woodlands, and forests.

Image availability was patchy but mostly adequate: 12 percent of Britain was not covered by winter data and much of the remainder was only covered by one winter scene in the study period. Sometimes, two summer scenes were needed to ensure near full coverage adding costs in time and image purchases.

Field reconnaissance offered a pragmatic solution to a significant problem, namely, that of covering large areas in order to maximize the diversity of information collected per scene. Field reconnaissance accounted for between 5 percent and 10 percent of the time taken in the mapping of Britain.

Maximum-likelihood classification worked, despite possible statistical problems, e.g., the uncertainty about the normal distribution in radiance values, the subjective choice and limited number of training areas, and, sometimes, the relatively few pixels in a training set (Kershaw and Fuller, 1992). The use of subclasses helped give closer adherence to a normal distribution. Summer-winter composite images gave improved cover distinctions and so better accommodated possible limitations in the training data. The iterative approach, with built-in checks, delivered the required results because problems were corrected *en route*. A fuller statistical evaluation would be desirable, but was not available within the S600 software package. It was felt that operational uses, once feasible, should not be delayed in the quest for an ever-better methodology.

The chosen classification may not satisfy all users. It is a compromise between the "simple but accurate" separation of few cover types and the "complex but impossible" distinction of many. The classes are based on tried and tested cover types of other surveys, agreed upon by end users, and shown in pilot exercises to be feasible. The hierarchical structure enables users to reconstruct their own simpler classes. Conversely, the subclass structure offers detail for specialist consultation.

Knowledge-based correction, taking account of context, offers a simple solution to the obvious criticism that per-pixel classifiers employ no intelligence in making a classification, and hence make ludicrous mistakes. Such mistakes often show as "noise" in the data which was substantially eliminated by the contextual masks.

The use of filtering algorithms to remove "noise" in the data is a regular practice. The choice of a filter which only removed isolated pixels was based on the observation that coarser filters rejected useful information. However, a range of options are applicable to the current cover maps, for those wishing to generalize further.

Quality of Results

Geometric correction procedures gave remarkably good spatial quality, suitable for wide-ranging applications of the data. However, minor geometric misregistrations of otherwise good land-cover maps were recorded as misclassification of pixels when comparing directly with ground or API maps, although the effect on areal estimates was minimal. Even when geometric misregistration was not a problem, discrepancies were largely associated with boundaries due to the difficulties of classifying mixed boundary pixels.

Many discrepancies between the Landsat and reference data were explained by differences in survey objectives and class interpretation. The field and aerial surveys concentrated on mapping boundaries, within which contents were assumed to be uniform. Based on Ordnance Survey maps, such surveys also exaggerated small linear features such as roads (which are shown at enlarged scale). Conversely, the Land Cover Map could neither identify boundaries nor the smaller linear features, but did record the within-field heterogeneity. However, its summary of cover on a 25-m grid imposed a spatial quantization which cannot be directly compared with continuously variable vector data. The division of continua of vegetation classes into a discrete number of types also imposed artificial quantizations on the results of each survey which showed up in comparisons. Misclassification was clearly a problem attributable to the Land Cover Map, but the field and air photo-maps also showed inconsistencies.

No survey could have delivered the "ground truth" needed for exact validation, but it is possible to assess the probable meaning of results obtained here. If, as seems likely, the original CS90 field survey was nearly "as good as" the quality assurance survey and each "correctly" recorded 90 to 95 percent of the landscape, they would have overlapped by around the measured 84 percent. If the Landsat survey achieved 80 to 85 percent success (a figure regularly achieved in pilot studies (Fuller *et al.*, 1989a; Fuller *et al.*, 1989b; Fuller and Parsell, 1990)), then the correspondence with the field survey would have been around 67 to 71 percent. These are the range of figures obtained if we allow for the obvious interpretation differences, with an element of temporal change. In conclusion, a realistic assessment of Land Cover Map accuracy is probably 80 to 85 percent.

Future Updates

The methods are in place to update the Land Cover Map of Great Britain on a regular basis. The "learning curve" has been "climbed" and a repeat survey might only take two-thirds of the 5 man-years devoted to the original survey. However, there are still a number of areas for future improvements. Improved registration of summer-winter composite images would improve accuracy levels. It might be possible to examine local correlations between summer and winter data, or to use edge detectors to better achieve local coincidence.

This project has built a library of spectral signatures for all major habitats in Britain, most recorded throughout the year. The data tell future users of TM what various cover types should look like at various seasons. Knowledge of spectral signatures, with correction for variable atmospheric absorption, could be used to make a fully automated classification of new images.

The Land Cover Map represents a "knowledge base" to help in future mapping. The original map might form the masks for knowledge-based corrections (e.g., providing a coastline). The map might help to define training areas. It might be used to allocate the classes in an unsupervised classification. The existing map might help segment an image for within-segment classification. New maximum-likelihood classifications could be checked against the original, and probability levels could be used to help decide whether changes were real or the result of error (original or new).

Ordnance Survey boundary data exist in digital form, yet we have been unable to use these in classification. The boundaries might help to achieve a better summer-winter registration. Outlines might be integrated with satellite data for improved segmentation and better within-segment classification. The procedure could define boundary pixels and allow their allocation by mixture modelling (Settle and Drake, 1993).

There is a need for greater cover detail. Some users require a knowledge of specific crops, or wish to identify unimproved agricultural grasslands. New generations of sensors will combine improved spatial resolution with enhanced spectral resolution. Technological developments should try to exploit radar's "all-weather" capability to supplement missing data: if SAR analyses were merely able to distinguish bare from vegetated surfaces, SAR would nonetheless serve a major role of the winter data, namely, to distinguish between semi-natural vegetation and cropped areas. These developments will, however, offer new problems which will require solution if maximum output is to be expected.

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